

History of the Rapid Chloride Permeability Test

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Corrosion of reinforcing steel is recognized as the predominant cause of bridge deck deterioration. The need for a more precise method to estimate the susceptibility of a bridge to corrosion led to the development of the rapid chloride permeability test (AASHTO T 277-89 and ASTM C 1202-91). The developers of the test describe its conception, development, and applications. Concepts of permeability as applied to concrete are discussed, and the need for a rapid measure of chloride ion penetration into concrete is addressed. The authors describe the development and testing of a field method based on forcing chloride ions to migrate toward reinforcing steel maintained at a positive potential and note its limitations. Concurrent development of a laboratory procedure based on similar principles is described, and results of a round-robin statistical evaluation of method precision are presented. Further evaluations, current applications, and limitations are also discussed.

In the mid-1970s FHWA began to publish a series of comprehensive reports (1-3) dealing with factors involved in corrosion of reinforcing steel in concrete. Corrosion of reinforcing steel had been recognized as the predominant cause of premature bridge deck deterioration, as demonstrated by field investigations carried out at a number of agencies in the 1960s (4,5). The FHWA reports related the onset of corrosion to the presence of chloride ions that penetrated through the concrete cover after deicing agents were applied to the bridge surface. Other factors, such as moisture content and oxygen, were also needed to support corrosion once initiated. Finally, because the chloride ions had to penetrate through the concrete in order to reach the reinforcing steel, the permeability of the concrete cover became a determining factor in the time-to-corrosion of the reinforcement.

Recognizing that the ability to measure a number of these factors in actual structures would allow a more precise estimate of the susceptibility of a given bridge deck to corrosion, FHWA supported a series of contracts designed to develop field instruments capable of measuring these parameters. Devices to measure in situ chloride (6) and moisture content (7) were developed. A method to rapidly (and nondestructively) measure the permeability of bridge deck concrete to chloride ions was also needed, and in 1977 FHWA let a contract with Construction Technology Laboratories of Skokie, Illinois, to develop such a device. (Note: Some individuals believe the term "permeability" is not appropriate when referring to the mechanism for chloride ion movement, but instead speak of concrete's "lack of resistance to chloride ion penetration.")

Because the dictionary defines "permeability" as "the quality of being able to be diffused through or penetrated," the authors believe the use of that term in this context is correct.) The development of the field device and subsequent widespread use of a laboratory method based on the same principles is the subject of this paper.

ORIGINS OF THE TEST METHOD

Literature Review

Considerable work in the area of concrete permeability had already been carried out at the time this research was initiated. A comprehensive literature review was conducted; much of the same material is covered in a more recent review by Collins et al. (8). These reviews indicate that most of the early work in permeability of concrete dealt with flow of bulk water through concrete under relatively high pressure heads, as such data were needed in design of concrete mixtures for hydroelectric and flood control projects. Classic papers in this field include those by Ruettgers et al. (9) and Cook (10). These and other studies demonstrated that the permeability of concrete could vary by as much as two orders of magnitude as the water to cement ratio (w/c) increases from 0.4 to more than 0.7.

The steady-state flow of water under a hydraulic gradient, as measured in the early studies, was deemed to be not relevant to the bridge deck situation. What was of interest was the penetration of chloride ions (derived primarily from sodium chloride deicing agents) to the vicinity of the steel. Except for the near-surface region of the concrete, where capillary forces (11) may be active under drying conditions, the predominant mechanism for transport of chloride ions in crack-free concrete is by ionic diffusion through the water-filled pore system. Studies by Clear (1-3), Monfore and Ost (12), Collepari et al. (13), Berman and Chaiken (14), and Kondo et al. (15) have demonstrated this mechanism and again verified the influence of w/c on the rate of chloride diffusion.

These measurements, however, involved either long-term ponding with chloride solutions and subsequent measurement of chloride concentration with depth or direct measurement of diffusion using classical diffusion cell techniques (16), both inappropriate to rapid field testing. This is not to say that the subject of field testing of concrete permeability had been totally ignored before 1977. By the early 1970s, for example, Levitt (17) and Figg (18) had developed devices that indicate the relative permeability of concrete to water or air. However, it was not at all certain whether such techniques would cor-

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relate with diffusion of chloride ions into concrete, which was the primary concern of FHWA. Highest priority was given to developing a method based on measurement of chloride ion penetration, as this would also serve as a direct field demonstration that low-permeability concretes under development at that time (19-21) could indeed retard the penetration of chlorides into bridge deck surfaces.

Genesis of the Method

A special case of diffusion occurs when an electric potential is applied across an electrolytic solution, free or contained within a porous material. The ions will then be transported toward the electrodes of the opposing sign (22). Ionic mobility is given by the following expression:

$$\mu = \frac{x}{t(dE/dx)} \quad (1)$$

where

- μ = ionic mobility ($\text{cm}^2/\text{V}\cdot\text{s}$),
- x = distance (cm),
- t = time (sec), and
- dE/dx = electric field strength (V/cm).

Using these principles, studies carried out in the mid-1970s (23,24) indicated that chloride could be extracted from a concrete slab quite rapidly by applying an external electric field between the concrete slab surface and the reinforcing steel.

It was reasoned that this technique could be used as a chloride permeability method if the polarity were reversed, that is, if the reinforcing steel were made anodic (positively charged); chloride ions, having a negative charge, would migrate into the concrete when the voltage was applied. After a suitable period of treatment, samples could be taken to verify the ingress of chloride by subsequent wet chemical analysis. This approach was called the applied voltage concept. A few preliminary experiments using thin membranes composed of cement pastes, aggregate materials, and mortars indicated that the concept was sound, and chloride ions could be forced to migrate through these materials in reasonably short periods of time. Furthermore, results were generally comparable to longer term experiments on the same materials that involved diffusion under conditions under which no voltage was applied across the membranes. (Note: Measuring how easily chloride ions can be forced to move through mortars or concretes electrically is not directly measuring chloride permeability; that such measurements correlate with the results of long term diffusion experiments means, however, that applied voltage methods can be regarded as indirect methods of measuring chloride permeability.) Experiments on concrete were then planned.

TEST METHOD DEVELOPMENT

Optimization of Test Parameters

The first task undertaken was optimization of the various test parameters (area of measurement, time of measurement, volt-

age level) within the context of a rapid and practical field method.

A drawing of the apparatus used in the preliminary studies is shown in Figure 1. A dc power supply applied a constant voltage between the copper screen and steel reinforcing mat.

Conventional reinforced concrete slabs were prepared at both high and low w/c ratios (0.35 and 0.60). Testing was conducted at voltages from 10 to 120 Vdc and over periods of time from 1 to 8 hr. Parameters evaluated included currents generated during the test, chloride content of the concrete slabs at various depths [up to 2 in. (50 mm)] after test, chloride content of the solution after test, and temperatures generated inside the slabs during test. The following conclusions were reached:

1. A test period of 6 hr at 80.0 Vdc offered the optimum test condition for distinguishing between concretes having high and low chloride permeabilities.
2. Up to 2.6 amperes of current was passed through a highly permeable concrete slab during the test period, compared with 1.8 amperes for a low-permeability slab.
3. After 6 hr of testing at 80.0 Vdc, approximately half as much chloride ion was detected $\frac{3}{4}$ in. (19 mm) below the surface of the low-permeability slab as was detected at the same depth in the high-permeability slab.
4. Whereas chloride concentration of the surface solution after testing could be measured in the laboratory, accurate field techniques did not exist at that time. Therefore, use of the change in concentration of the surface solution as a measure of permeability was abandoned.
5. Temperature rise in the slabs during testing was significant, being greatest for the high-permeability concrete. However, in full-scale bridge decks this was not expected to present a problem because of the much larger heat sink, as compared with small laboratory specimens.

Application to Other Concretes

The promising initial results led to an expanded test program on a variety of concrete slabs. These slabs were prepared by FHWA laboratories from a number of concrete types. Slabs were tested in three different states, as-received (after conventional curing for each type of concrete, e.g., 14 days with moist burlap covering for ordinary portland cement concrete),

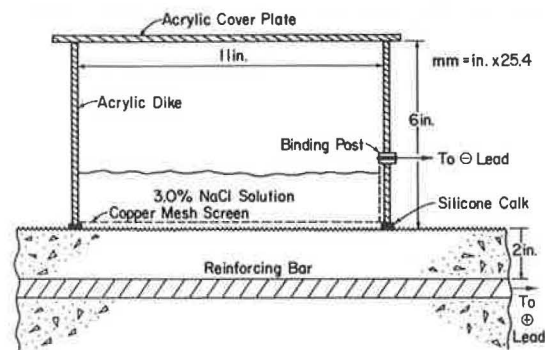


FIGURE 1 Apparatus used in preliminary studies.

after approximately 3 months of moist storage, and after 2 weeks of forced-air drying at 130°F (54°C). The test protocol throughout this phase consisted of a 6-hr application of 80.0 Vdc between a 3 percent sodium chloride solution ponded on top of the slab and a mat of reinforcing bars located 2 in. (50 mm) below the slab surface.

Representative examples of the behavior of current flowing through the slabs during the test period are shown in Figure 2. In the highest permeability concrete tested ($w/c = 0.6$), a peak occurred in the plot of current versus time, whereas for the other concretes current increased continuously with time. The magnitude of the current flow was generally proportional to the expected relative permeabilities of the various concretes.

The plots of current versus time were also integrated to obtain the total electric charge (in coulombs) passing through the slabs during the test period. In addition, after chloride analyses were obtained at 1/4-in. (6-mm) depth increments after each test, the plots of chloride content versus depth were integrated to obtain an estimate of total integral slab chloride content. Results for the as-received slabs after testing are presented in Table 1. The various concretes were placed into four convenient major groups. The first, conventional concretes, exhibits relatively high total chloride levels and charge passed. In the next group, which encompasses latex-modified and Iowa concretes, values of total chloride and charge passed are about 20 to 30 percent lower than the best of the conventional concretes. The third group, internally sealed concretes, showed a dramatic drop in both parameters. (Internally sealed concrete was an experimental material developed in the 1970s made by mixing small, discrete wax particles into conventional portland cement concrete mixtures. After curing, the concrete was heated and the wax melted and flowed into the capillaries and bleed channels; when the heat source was removed, the wax cooled and produced a low-permeability concrete.) Note that when internally sealed concrete was not heat treated, its permeability was the same as conventional concretes. The final group, polymer-impregnated and polymer concrete, shows negligible permeability to chlorides.

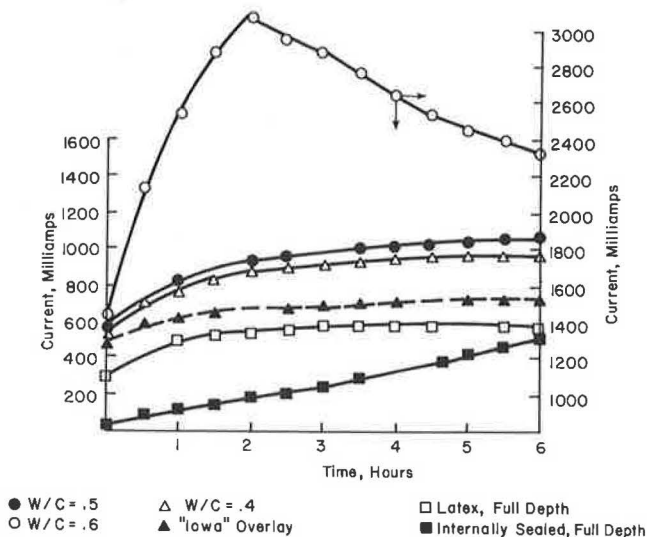


FIGURE 2 Current flow versus time through FHWA slabs.

TABLE 1 PERMEABILITY CHARACTERIZATION PARAMETERS

Description	Total Integral Chloride	Total Charge Passed (Coulombs)	Chloride Permeability
$w/c = 0.60$	0.77	52,570	High
$w/c = 0.50$	0.56	39,380	High
$w/c = 0.40$	0.37	20,410	High
Latex - Overlay	0.37	16,950	Moderate
Latex - Full Depth	0.27	8,670	Moderate
Iowa - Overlay	0.31	15,270	Moderate
Internally Sealed - Full Depth - Heated ^a	0.10	5,770	Low
Internally Sealed - Full Depth - Unheated	0.93	36,070	High
Internally Sealed - Overlay - Heated ^b	0.09	3,020	Low
Internally Sealed - Overlay - Unheated	0.47	22,418	High
Polymer Impregnated	--	0	Very Low
Polymer Concrete Overlay ^b	--	0	Very Low

^aSlabs tested in moist condition only.
^bSlabs not sampled for chloride.

Correlation with 90-Day Ponding Results

In the late 1970s, the most commonly used procedure for determining chloride permeability of concrete was that specified in AASHTO T 259, Resistance of Concrete to Chloride Ion Penetration. In T 259, concrete samples are ponded with a 3 percent sodium chloride solution for 90 days, after which the chloride content of the concrete at various levels in the sample is established by wet chemical analysis. This ponding procedure was applied to companion specimens prepared along with specimens used in the evaluation of the applied voltage test. Correlation analyses (using linear regression techniques) were performed between the data in the second and third columns of Table 1 and the results of 90-day ponding tests.

The correlations indicated that the closest relationship was between the charge passed (coulombs) in the rapid test and the total integral chloride in the 90-day test. A correlation coefficient of 0.92 was calculated. Data obtained on the moist-cured specimens were also encouraging. However, when the applied voltage technique was tested on a set of slabs subjected to forced air-drying for 2 weeks at 130°F (54°C), serious problems were encountered. The values of charge passed and total chloride were much lower than those recorded on companion slabs tested in the as-received or moist conditions. It was obvious that the drying reduced the moisture content of the concrete to such an extent that the amount of current that could be passed through the slabs was limited by the high electrical resistance caused by the drying. Therefore, a method for preconditioning the test area to a moisture content close to that of the original concrete was needed.

To develop preconditioning procedures, the test apparatus was modified to enable a vacuum of -25.5 in Hg (15.0 kPa absolute pressure) to be drawn over the surface of the slab by use of a vacuum chamber sealed to the slab surface by silicone-based caulk. Various resaturation schemes were evaluated, and the following approach was found to be most effective.

1. A vacuum is maintained over the test area for 60 min. Limewater is then introduced into the chamber, and the vacuum is maintained for another 60 min.

2. The vacuum is broken, and the limewater is heated and held at 140°F (60°C) for approximately 18 hr.

3. The limewater is removed, the 3 percent sodium chloride solution is poured into the chamber, and the applied voltage test is conducted as previously described.

This procedure was incorporated into the design of the prototype and was used in all succeeding work.

Development of Field Prototype

Many workers who routinely use the AASHTO T 277 laboratory technique are not aware that a field version of the procedure was developed and tested more than 10 years ago. This device incorporated the features of the laboratory components into a single package. The field instrumentation consisted of three separate modules, one to vacuum saturate the concrete before test, the second to apply the voltage to the salt solution on the concrete surface, and the third (the electronics package) to provide the voltage source and accumulate the data. A detailed description of the instrumentation can be found in a report by Whiting (25).

The field test procedure can be conveniently separated into four stages:

1. Location of reinforcing steel and bonding of test dike,
2. Vacuum saturation and heating of test area,
3. Applied voltage test, and
4. Optional chloride sampling.

Each test takes 2 full work days; if two dikes are used, four tests can be completed in 1 work week (modifying the electronics package could further increase productivity by allowing two or more tests to be conducted at the same time). Stage 2 requires overnight operations; however, the unit may be left unattended during this period.

Before proceeding to actual field testing, the prototype was tested on slabs intermediate in size between the small specimens tested in the initial phases of the project and full-scale bridge decks. This allowed evaluation using a more realistic heat sink and also allowed the evaluation of a number of variables within a single slab. Variables studied in detail were the following:

1. Concrete cover,
2. Ambient test temperature,
3. Geometry of reinforcing cages, and
4. Presence of chloride in concrete before test.

Results of these tests indicated that (a) deviations of ± 1 in. (25 mm) in concrete cover from the nominal 2-in. (50-mm) test cover caused deviations of ± 25 percent in charge passed; (b) reinforcing bar size and cage geometry had no significant effect on charge passed; (c) charge passed increased with an increase in initial slab temperature; and (d) initial slab chloride contents of up to 5 lb/yd³ (3 kg/m³) had little effect on charge passed.

Field testing was carried out on a conventional concrete bridge deck (just constructed) and on an older deck that had recently been overlaid with dense low-slump concrete (26).

Results on the conventional deck fell within the ranges to be expected from a bridge deck concrete with w/c between 0.4 and 0.5, but interpretation of test results on the overlay was complicated by varying relative thicknesses of overlay and substrate at the different test locations.

In addition, the presence of chlorides in the aggregates appeared to interfere with the chloride analysis and subsequent calculation of integral chloride values. Finally, a series of four in situ tests required that one lane of traffic be closed continuously for 5 days. This is quite expensive when traffic control requirements are considered. Although workable, the field test appeared to need further development, and, in any case, was somewhat impractical in terms of operation on in-service structures. As an alternative, a laboratory test, described in subsequent sections, was developed.

ADOPTION OF A LABORATORY TEST PROCEDURE

Description of the Laboratory Method

In view of the limitations on the field device, a laboratory version of the apparatus was developed. It should be noted that the laboratory test was developed originally as an alternative to the field test, to be used in those instances when it was not practical to employ the in situ device. It was not viewed as an accurate, standard laboratory test to determine the absolute permeability of a given concrete; the objective of the original research project had simply been to develop a rugged, in situ indicator of permeability. Because the laboratory test was viewed as a fallback, it was not developed and tested nearly as thoroughly as the field method, and no systematic investigations were carried out of the many variables that might influence the test.

The new device was called the applied voltage cell and is shown in Figure 3. The cell is machined out of solid acrylic plastic (e.g., polymethylmethacrylate) and allows for two reservoirs of approximately 200 mL capacity to be fitted onto either face of a 4-in. (102-mm) diameter core by use of a rapid-setting silicone compound. One reservoir is filled with 0.3 M NaOH, the other with 3.0 percent NaCl. The core specimen [usually 2 in. (51 mm) thick] is coated on its periphery with epoxy and vacuum saturated for 18 hr before test. The core is then sealed between the cell halves, the reservoirs are filled, and the specimen subjected to an applied voltage of 60.0 Vdc for 6 hr. Current is monitored during the 6-hr period, and, as in the field test, the integral of current over time yields a value of charge passed (in coulombs) during the test.

The lab procedure was applied to cores taken from the same set of slabs used in development of the field device. In addition to the charge passed parameter, the amount of chloride ion present in the positively charged half of the cell, representing the chloride that had passed entirely through the sample during the test period, was also measured. Attempts were also made to construct chloride profiles by obtaining thin slices from the cores after the test was completed; however, this process was tedious and not appropriate for inclusion in a rapid test procedure.

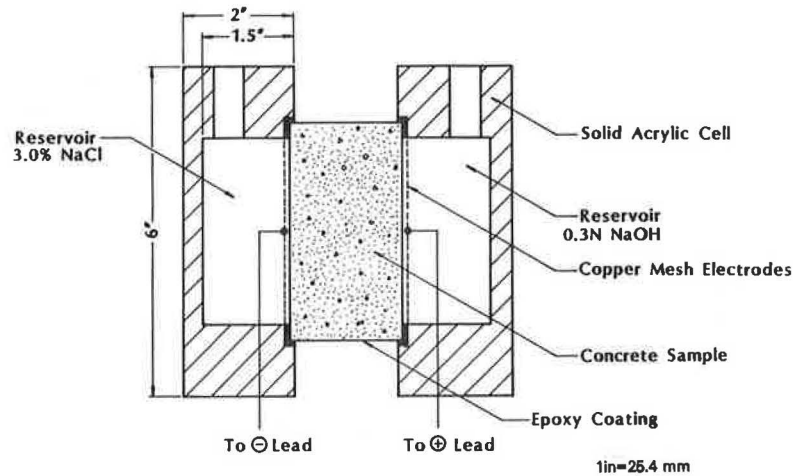


FIGURE 3 Schematic drawing of applied voltage cell.

As had been done for the slab tests, correlation analyses were run between charge passed through the cores and the results of 90-day chloride ponding on companion slabs. The correlation coefficient for the charge passed through cores compared with the integral chloride contents of the companion slabs was 0.83. This was somewhat less than the correlation coefficient for the charge passed through slabs versus integral chloride content, which was 0.92. The difference was perhaps due to the limited surface area included in the core test, as opposed to the approximately 1 ft² (0.09 m²) of surface included in the slab tests. This indicated that multiple samples would need to be tested in order to obtain a more representative test area. The coefficients of variation for 6-sample groups prepared from batches of high w/c (0.6) and latex-modified concretes were each approximately 6 percent.

Standardization of the Laboratory Method

In 1982, researchers presented the laboratory method to AASHTO for consideration as a standard test method. The method had come to be referred to as the rapid chloride permeability test (RCPT), or the coulomb test, and was immediately adopted by AASHTO and given the designation T 277-83, Rapid Determination of the Chloride Permeability of Concrete. The method presented for standardization and adopted was essentially the material contained in Appendix 1 of the original FHWA report (25).

This version of the test method included a table to interpret the results; it is presented here as Table 2. In the AASHTO version, only the charge passed (in coulombs) is used as an indicator of permeability. Many users of the method believe that these values represent a large data base of concrete tests and are typical of what to expect in testing concretes of the types described. In fact, the table was constructed from results obtained on single cores of each concrete type, taken from the slabs originally supplied by the FHWA. As a further caution, in Appendix 1 of the FHWA report, the following advice is given: "The effect of such variables as aggregate type and size, cement content and composition, density, and other factors have not been evaluated. We recommend that persons

using this procedure prepare a set of concretes from local materials and use these to establish their own correlation between charge passed and known chloride permeability for their own particular materials. The values given in Table I [Table 2 in this paper] may be used as estimates until more data has been developed by a number of agencies on a wider range of concretes." Although further testing of some of these variables has since been carried out, it has been limited, and the values in Table 2 still must be applied with extreme caution. The concretes listed in the third column were intended to serve as examples of concretes that might typically give the coulomb values in the first column. Because of the many other factors that may affect chloride permeability, this simple correspondence does not always hold true.

In late 1991 the laboratory method was also adopted by ASTM, as C 1202, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. Although some differences exist between the ASTM and AASHTO versions, none are significant; the basic test procedures are identical.

One important feature of both standard versions of the test method is the precision statements, which were developed from an interlaboratory study carried out in late 1985. A total of 11 laboratories participated in this round-robin study to develop values for within- and between-laboratory precision.

TABLE 2 CHLORIDE PERMEABILITY BASED ON CHARGE PASSED

Charge Passed ^a (Coulombs)	Chloride Permeability	Typical of
> 4,000	High	High water-cement ratio, conventional (≥ 0.6) PCC
2,000 - 4,000	Moderate	Moderate water-cement ratio, conventional (0.4-0.5) PCC
1,000 - 2,000	Low	Low water-cement ratio, conventional (< 0.4) PCC
100 - 1,000	Very Low	Latex-modified concrete Internally sealed concrete
< 100	Negligible	Polymer impregnated concrete Polymer concrete

^aCoefficients of variation for replicate specimens from a single batch were approximately 6 percent.

Two conventional and two latex-modified concrete mixtures were included, and each laboratory tested triplicate specimens from each mixture. Detailed results can be found in publications by Mobasher and Mitchell (27,28). The following are the precision statements that were developed and are now part of both standards:

- Single-operator precision: The single-operator coefficient of variation of a single test result was found to be 12.3 percent. Therefore, the results of two properly conducted tests by the same operator on the same material should not differ by more than 35 percent.

- Multilaboratory precision: The multilaboratory coefficient of variation of a single test result was found to be 18.0 percent. Therefore, results of two properly conducted tests in different laboratories on the same material should not differ by more than 51 percent. The averages of three test results in two different laboratories should not differ by more than 29 percent.

These precision estimates (especially that for single-operator essentially a measure of within-test precision) seem somewhat high when compared with other tests that are more commonly used to assess quality characteristics of concrete. For instance ACI 214 (29) categorizes within-test coefficients of variation for field control testing as poor if they exceed 6.0 percent. Mobasher and Mitchell (27) suggest the variabilities from the round-robin may have been higher than they should have been because laboratories deviated from details of the AASHTO T 277 procedure and from the round-robin instructions. Several of the laboratories were relatively new users of the method and apparently did not recognize the importance of some aspects of the test.

Although Hooton (30) notes that permeability of concrete is, in general, a more variable quantity than strength, there is reason to believe that significant improvements can be made in the precision of the test. Because the test is now an ASTM standard, laboratories will presumably more closely follow the detailed ASTM version of the method. Between-laboratory variations would likely be reduced if the method were added to the list of those inspected by laboratory evaluators such as the Cement and Concrete Reference Laboratory during their periodic tours. Finally, after researchers evaluate the ruggedness of various test parameters and make additional refinements in the procedure, improved precision would be expected and another interlaboratory study might be appropriate.

Current and Future Applications of the Method

Since its adoption by AASHTO as an interim test method in 1983, the RCPT has come into increasing use in the areas of concrete materials research, development and testing of concrete mixtures, and acceptance of job-site concrete. The technique apparently gives users the ability to measure a property of concrete that heretofore has been relatively difficult and time-consuming to determine. The availability of commercial instrumentation designed specifically to conduct AASHTO T 277 or ASTM C 1202 now makes it possible for almost any test lab to obtain a permeability value. A word of caution is

advised, however, because the quantity measured by the RCPT is not permeability in the strictest sense, but is instead an indication of permeability based on the ability of a given concrete specimen to conduct electric current. Any materials that cause concrete to be more (or less) conductive will increase (or decrease) the value obtained using the RCPT, irrespective of the effects that such materials or treatments have on actual permeability, diffusion, or other mass transport phenomena.

In spite of these limitations, the utility of the RCPT for gaining an understanding of the effects of materials and treatments on concrete permeability has been demonstrated by the large numbers of studies where it has been successfully used. The reader is referred to its use in studies of concrete consolidation (31), of the effects of aggregates (28) and cements and pozzolans (32,33) on permeability, and of specialty concretes (34–36) and coatings and sealers (37,38). In these and most other studies the RCPT has been the sole method used for determination of permeability to chloride ions, other techniques being too costly or time-consuming. However, in those instances in which other measures of permeability have been used, agreement with the RCPT has generally been quite good.

Were it not for two developments, the RCPT might still be a laboratory curiosity limited to occasional research studies. The first of these, its standardization by AASHTO, has already been noted. A number of state highway agencies began to use the test immediately, especially for product and mixture design evaluation. The second development that has led to widespread use of the method is the large growth in the use of silica fume as a concrete admixture in the mid- to late 1980s. Holland (39) noted that more than 350,000 yd³ (270,000 m³) of silica fume concrete was placed in 1986 alone, and its use is expected to increase annually. Its primary application is for reducing permeability of concrete to chloride ions in such structures as bridge decks and parking garage slabs. Although the RCPT is an indirect method, Luther (40) noted that since 1986 it has increasingly been specified for use in parking garage slab placements and on shotcrete repair jobs. In many cases, an arbitrarily chosen value of charge passed (in coulombs) is selected as the maximum design value, usually between 700 and 1,000 coulombs. Trial mixtures are usually tested to see if this limit can be met. On the actual job, samples are obtained either in the form of cast cylinders or as cores taken from the cured slabs. Testing is carried out at various ages, from 28 to 90 days, with a 42 days apparently the most common. Accelerated curing, using techniques similar to ASTM C 684-89, Standard Test Method for Making, Accelerated Curing, and Testing Concrete Compressive Test Specimens—Procedure B—Boiling Water Method has been used. Acceptance is based on the average value of charge passed being less than the specified limit. Statistically based acceptance schemes are nonexistent. In the authors' opinion, further work on definition of acceptable limits, development of statistical acceptance schemes, and improvement in the precision of the test must be done before this technique can be equitably applied to acceptance of silica-fume and other types of concrete. Users must also recognize that chloride permeability depends not only on the mix design and the component materials, but also on such aspects of construction as degree of consolidation and type and extent of curing.

SUMMARY

In the late 1970s, in response to the needs of the highway engineering community, a method was developed that afforded an in situ indication of the chloride permeability of reinforced portland cement concrete bridge structures. Although results obtained via this method correlated well with long-term ponding of chloride solutions, practical considerations made it more pragmatic to obtain cores from the structure of interest and test these cores using a laboratory version of the method. This laboratory version was standardized by AASHTO in the early 1980s, and with the increasing use of silica fume in the latter half of the decade has been increasingly applied to design, testing, and acceptance of such mixtures. Comparison studies have shown the test method, at least in its original version, to be less precise than methods generally used in acceptance of concrete, such as compressive strength. Although the method is adequate for research and materials development purposes, further standardization and development of statistically based decision schemes are needed before the technique can be equitably applied as an acceptance tool.

ACKNOWLEDGMENTS

Over the years, many people have contributed to the initial conception, development, standardization, and application of the method discussed here. Many are recognized as sources of reference for this paper. Others involved in the initial development include William F. Perenchio, who codeveloped the initial concept; Robert Carver, who designed and assembled the electronic instrumentation package; and Kenneth C. Clear, who assisted in many technical aspects of the FHWA effort. The authors also acknowledge the many insights gained by the users of the method, and especially would like to thank Mark Luther and Neal Berke for their constructive criticisms based on their opportunities to apply the method in a variety of circumstances.

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