The Rapid Chloride Permeability Test and Its Correlation to the 90-Day Chloride Ponding Test

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This paper reviews documents referenced by ASTM C1202, "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," and explores the correlation of ASTM C1202 to AASHTO T259, "Resistance of Concrete to Chloride Ion Penetration." The procedure outlined in ASTM C1202 is based on the AASHTO Test Method T277, "Rapid Determination of the Chloride Permeability of Concrete," initially developed in 1981. Chloride penetration in both ASTM C1202 and AASHTO T277 is expressed as charge passed, or coulombs. The scope of ASTM C1202 states that this method is applicable to concretes in which a correlation has been established between the coulomb value and the amount of chloride ingress. This correlation testing is rarely performed by specifiers or researchers. Thus, selection or rejection of concrete based solely on ASTM C1202 can result in improper decisions and the rejection of concrete known to be durable. Based on the review of the documents referenced in ASTM C1202, it is concluded that reliable and proper correlations do not exist between the rapid test procedure results and 90-day ponding test results. The ASTM C1202 or AASHTO T277 test procedures should not be used in specifications without proper correlation to long-term tests. It is recommended that the table relating chloride penetration to coulomb values in these test procedures be removed since it is inaccurate and can be misleading.

The American Association of State Highway and Transportation Officials (AASHTO) Test Method T277, "Rapid Determination of the Chloride Permeability of Concrete,"[1] was adopted in 1983. Virtually the same test procedure was designated in 1991 by the American Society of Testing and Materials (ASTM) as C1202, "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration."[2]

In this ASTM test, one surface of a water-saturated concrete specimen is exposed to a sodium chloride solution, and the other surface to a sodium hydroxide solution. A 60-volt DC electrical potential is placed across the specimen for a six-hour period. The electrical charge (in coulombs) passed through the concrete specimen in that time represents its "rapid chloride permeability." The ease and speed of this six-hour test method has caused it to largely replace other methods of measuring chloride penetration into concrete, such as the 90-day ponding test of AASHTO T259, "Resistance of Concrete to Chloride Ion Penetration."[3]

The AASHTO T259 90-day ponding test was used to evaluate chloride penetration of concrete for many years prior to adoption of the rapid test (AASHTO T277 or ASTM C1202). Permeability, diffusion and absorption are the important physical processes controlling chloride penetration into concrete during the 90-day ponding test, whereas electrical resistivity appears to be the primary factor controlling charge passed during the rapid test. The sensitivity of the two methods to these different physical processes may cause significant variations in the ranking of the permeabilities of various concretes. As stated in the scope of ASTM C1202, the rapid test procedure is applicable to types of concrete in which correlations have been established between this rapid test procedure and long-term chloride ponding procedures, such as AASHTO T259.

Experts who use ASTM C1202 understand that the test is really a measure of the concrete resistivity. Concrete resistivity can be determined more easily using simple AC resistivity measurements. The initial reading after the power supply is activated in the ASTM C1202 test can also be used to calculate resistivity. There is no need to continue the test for six hours, and changes in the currents during this time are most likely due to increases in temperature and not chloride penetration. If the electrical resistivity of concrete is related to chloride permeability, then a test for electrical resistivity can be developed which is much quicker and simpler than ASTM C1202.

The rapid test method, ASTM C1202, is now commonly required by construction project specifications for both precast and cast-in-place concrete. An arbitrary value of less than 1000 coulombs is typically selected by the engineer or owner. This rating, usually chosen from the scale shown in Table 1 of ASTM C1202 and AASHTO T277, is characterized as "very low" chloride ion penetrability (see Table 1). Trial mixtures are typically tested to determine if the specified maximum charge passed can be met.

Based on the authors' experiences, the AASHTO T259 90-day ponding test is rarely specified for construction projects; therefore, correlation with rapid test method results for construction projects as required by the scope of ASTM C1202 is rarely made. Incorrect choices can be made by engineers who rely solely on the ASTM C1202 test without proper correlation to long-term tests.

The new ASTM C1202-91 test method document contains five references[4-8] that discuss coulombs passed data and chloride penetration data from ponding tests. These five references, as well as other references, are reviewed and comments are made on the applicability of the rapid test procedure.

REVIEW OF FIVE REFERENCE PAPERS IN ASTM C1202

ASTM C1202 Reference 1 — Rapid Determination of the Chloride Permeability of Concrete[4]

ASTM C1202 is essentially the rapid test method devised during the research which was reported in 1981. That research, which was undertaken for the Federal Highway Administration (FHWA), established an initial correlation between the rapid six-hour test method and the 90-day ponding test method, AASHTO T259. This limited initial research provided the correlation data shown in Table 1 of AASHTO T277, in many subsequent research papers between 1981 and 1993, and eventually in ASTM C1202. The test program was based upon tests on a *single* core of each of the concrete types listed here:

Concrete type	Water-cement ratio
Conventional concrete	0.6, 0.5, 0.4
Latex-modified concrete (LMC)	0.40
Iowa low slump concrete	0.33
Internally sealed wax bead concrete (heated and not heated)	0.55
Polymer impregnated concrete (PIC)	0.50
Polymer concrete (PC)	n/a

During the past 12 years, many researchers and writers of construction specifications have utilized the correlation shown in Table 1. A review of numerous American Concrete Institute (ACI) and ASTM publications[10-19] was performed by Wiss, Janney, Elstner Associates, Inc., to determine if other researchers had verified this preliminary correlation. Very few did. These numerous papers often contained a table similar to Table 1 and used it to reach conclusions regarding penetrability of chloride based solely on the rapid six-hour test data.

A method for interpretating the 90-day ponding chloride content profile data termed "total integral chloride (I)" was presented. This value was calculated using the acid-soluble chloride contents at 0.2 in. (5 mm) intervals from the surface of the ponded specimen to a depth of 1.6 in. (41 mm). This allowed chloride penetration data from the 90-day ponding test to be presented as a single value. This dimensionless value varied from about 0.15 to 1.6. The total integral chloride represents the total quantity of chloride from the surface to a depth of 1.6 in. (41 mm).

Table 1 of this paper shows values

Table. 1. Reference 1 correlation data.

Charge passed (coulombs)	Chloride permeability	Type of concrete	Total integral chloride to 1.6 in. depth after 90-day ponding test
>4000	High	High water-cement ratio, conventional (≥0.6) PCC*	>1.3
2000 – 4000	Moderate	Moderate water-cement ratio, conventional (0.4 to 0.5) PCC*	0.8 to 1.3
1000 – 2000	Low	Low water-cement ratio, conventional (<0.4) PCC*	0.55 to 0.8
100 – 1000	Very low	Latex-modified concrete Internally sealed concrete	0.35 to 0.55
<100	Negligible	Polymer impregnated concrete Polymer concrete	<0.35

* Portland cement concrete.
Note: 1 in. = 25.4 mm.

of *I* from the initial 1981 paper.[4] The data and the linear regression plot for the correlation of *I* and coulomb values are shown in Fig. 1. The correlation coefficient (R) was 0.83. The data shown in Fig. 1 exhibit large variations within the 700 to 1300 coulombs range commonly specified for construction projects. The correlation between charge passed, or coulombs, and chloride penetration following 90-day ponding based on this 1981 paper is shown in Table 1.

The polymer concrete (PC) and polymer-impregnated concrete (PIC) produced essentially zero "coulombs passed" values, yet these two concretes had measurable and relatively high total integral chloride values of 0.16 and 0.34 during 90-day ponding tests, dominantly controlled by chloride in the 0 to ⅝ in. (0 to 16 mm) depth interval. These two concretes were classified as having "negligible chloride permeability," as shown in Table 1.

ASTM C1202 Reference 2 — Permeability of Selected Concretes[5]

This 1988 study investigated the effect of one- and seven-day moist curing periods and the concrete water-cement ratio on chloride permeability. Triplicate specimens were cast from conventional non-air-entrained concretes with water-cement ratios of 0.29 to 0.75. A single concrete mixture containing 13 percent silica fume by weight of cement was also made, at a water to cementitious ratio of 0.26. The researcher concluded that:

- For the mixtures tested in this investigation, the variable having the greatest effect on permeability was the water-cement ratio.
- Concretes produced at water-cement ratios of less than 0.30, especially when silica fume was utilized, were virtually impermeable to water and chloride ions.
- Amounts of chloride ion detected within the first 1.5 in. (38 mm) of concrete, after 90-day ponding with sodium chloride solution, increased by a factor of 10 as water-cement ratios were increased from 0.26 to 0.75.

The paper presented only average chloride ion contents for the 12 test conditions. We used the reported average chloride ion contents and calculated the total integral chloride value *I* for each test condition. The data relating the results from the two test methods are plotted in Fig. 2. The data points result in a linear plot. Fig. 2

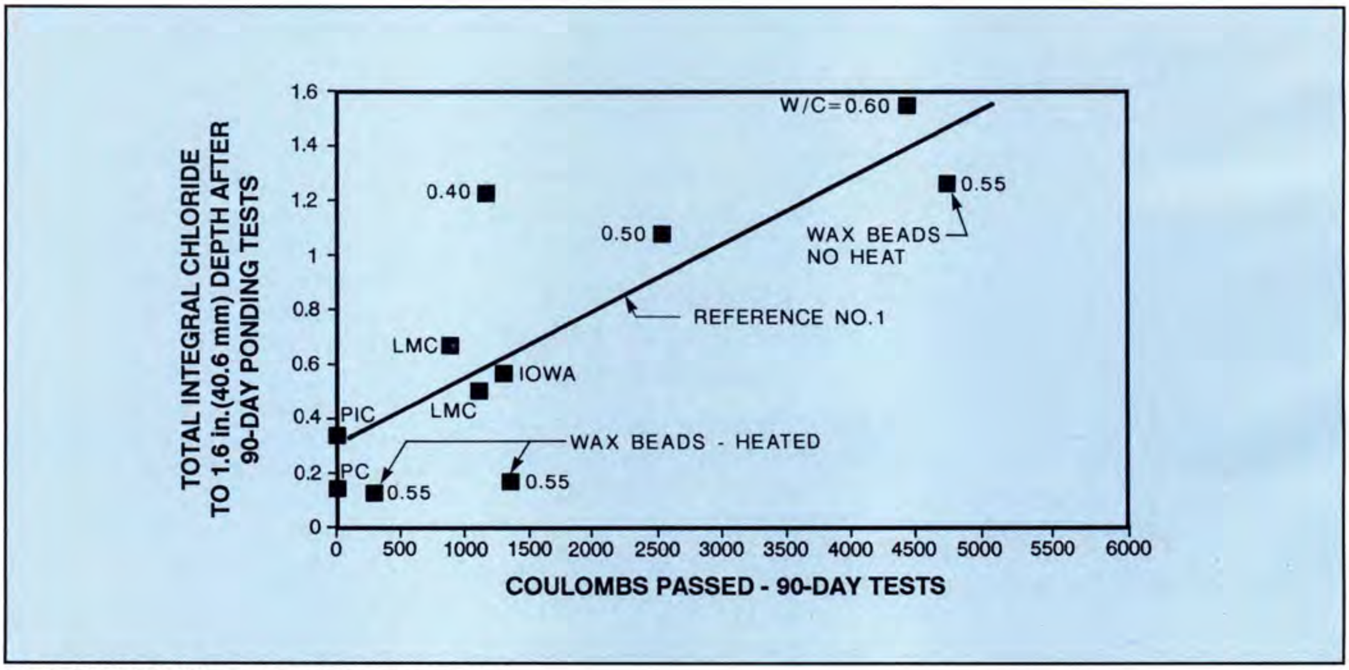

Fig 1. ASTM C1202 correlation data from Ref. 1.

also shows the line of best fit for the Refs. 1 and 2 data.

The data in Fig. 2 show that the two conventional concretes at 0.26 and 0.29 water-cement ratios, one with and one without silica fume, had calculated *I* values of only 0.10 to 0.16. These values are much lower than the PC and PIC concretes shown in Fig. 1, which previously had been judged as having "negligible permeability" based upon *I* values of less than 0.16 and 0.34 as reported in 1981.[4]

Concrete with water-cement ratios of 0.40 to 0.44 are commonly specified for parking garages and bridge decks. In ASTM C1202 Ref. 1,[4] the conventional concrete with a water-cement of 0.40 had a coulomb value of 1200 and an *I* value of 1.2, shown in Fig. 1. If a good correlation exists for the Ref. 1 data, a concrete with a charge passed of 1200 coulombs would be estimated as having an *I* value of 0.6. However, as shown in Fig. 2, 0.40 water-cement concretes in ASTM C1202 Ref. 2[5] have *I* values of about 0.48 and coulombs passed values of about 3000 and 4000.

These 0.40 water-cement ratio concretes would be classified as having moderate permeability based upon coulomb values, yet they would be classified as having very low permeability based upon their *I* values. The 0.29 water-cement ratio conventional concrete would be classified as having a very low-to-low permeability based upon coulomb values of about 900, yet it would be classified as having a negligible permeability based upon *I* values of about 0.16. These *I* values, measured on the 0.29 conventional water-cement ratio concrete, are lower than the 0.34 and 0.16 values measured on the PIC and PC concretes.[4]

The 0.29 water-cement ratio conventional concrete coulomb values of about 900 are approximately 16 times higher than the 0.26 water-cement ratio silica fume concrete, which had coulomb values of about 60. Yet, the *I* values for the 0.29 water-cement ratio mixture were only 1.5 times greater, and both had extremely low *I* values.

The *I* values of 0.16 to 0.50 were measured on these conventional 0.29 to 0.40 water-cement ratio concretes. Based upon *I*, Table 1 would classify these 0.29 to 0.40 water-cement ratio conventional concretes as having negligible chloride penetrability, even though the coulomb values ranged from 900 to 4000. The correlations for each study are much different and significant scatter occurs when combined. Clearly, the correlation between chloride ponding and charge passed is dubious, and the magnitude of the differences is misleading.

ASTM C1202 Reference 3 — Resistance to Chloride Infiltration of Superplasticized Concrete as Compared With Currently Used Concrete Overlay Systems[6]

This 1989 paper discussed the correlation between the rapid and ponding test methods for newly cast, low water-cement ratio concretes used for bridge overlays at construction sites in Ohio. Tests were made on 10 low water-cement ratio concretes containing high-range water-reducers (HRWR), two each from five sites; 10 latex-modified low water-cement ratio batches, two each from five sites; and two silica-fume modified batches from one site. Each concrete was tested using duplicate AASHTO T277 and singular AASHTO T259 test specimens.

A total of 44 rapid electrical tests were made, with 22 corresponding 90-day ponding tests. The single silica fume concrete utilized during this research had a silica fume content of 15 percent, generally considered high for typical construction projects. The concretes containing HRWR and silica fume were moist-cured for 42 days. The latex-modified concrete (LMC) was moist-cured for two days and then air-dried until age 42 days. Testing started at age 42 days.

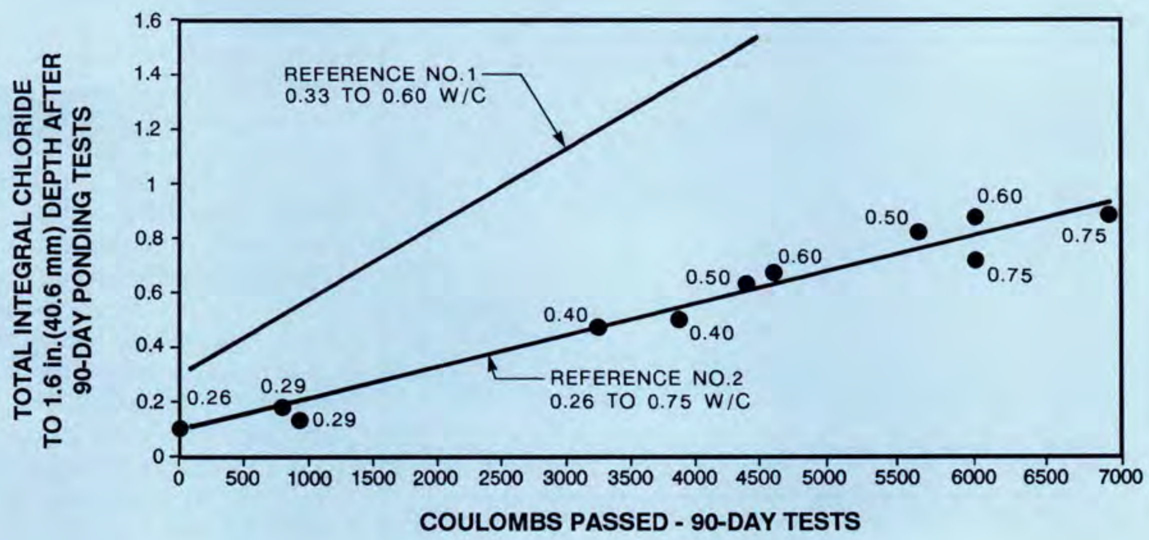

Fig. 2. ASTM C1202 correlation data from Refs. 1 and 2.

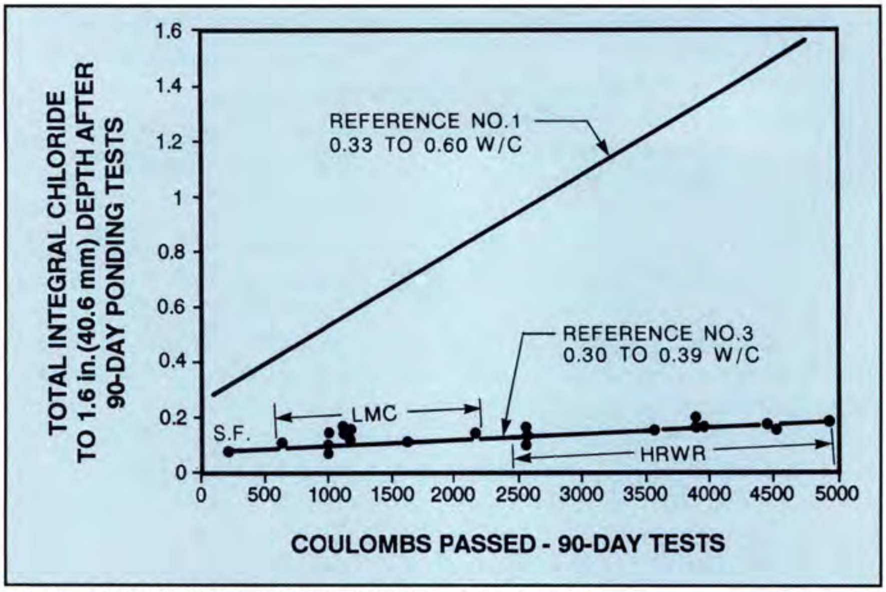

Fig. 3. ASTM C1202 correlation data from Refs. 1 and 3.

The exact water-cement ratios for these various concrete mixtures were not reported. However, the paper discusses that these concrete types generally have the following low water-cement ratios:

Concrete overlay type	Usual water-cement ratio
HRWR modified	0.30 to 0.32
Latex modified	<0.39
Silica fume modified	0.30

The measured data for these 0.30 to 0.39 water-cement ratio concretes are shown in Fig. 3. The correlation coefficient was 0.81. The *I* values for the 22 concretes were all extremely low, from 0.05 to 0.15. While all these concretes would be classified as virtually impermeable based upon *I*, coulomb values ranged from 250 to 5000. These data challenge the validity of the rapid test method in indicating relative chloride permeability classifications, based upon Table 1 shown in ASTM C1202.

The 10 latex-modified concretes produced coulomb values ranging from about 700 to 2200, and the 10 HRWR concretes had values ranging from 2500 to 5000 coulombs. The two silica fume concretes each had a 250 coulomb value. The average 3600 coulomb value for the 10 HRWR concretes is 14 times the silica fume concrete value of 250 coulombs, yet the average *I* value for the 10 HRWR concretes is only two times the *I* value for the silica fume concrete.

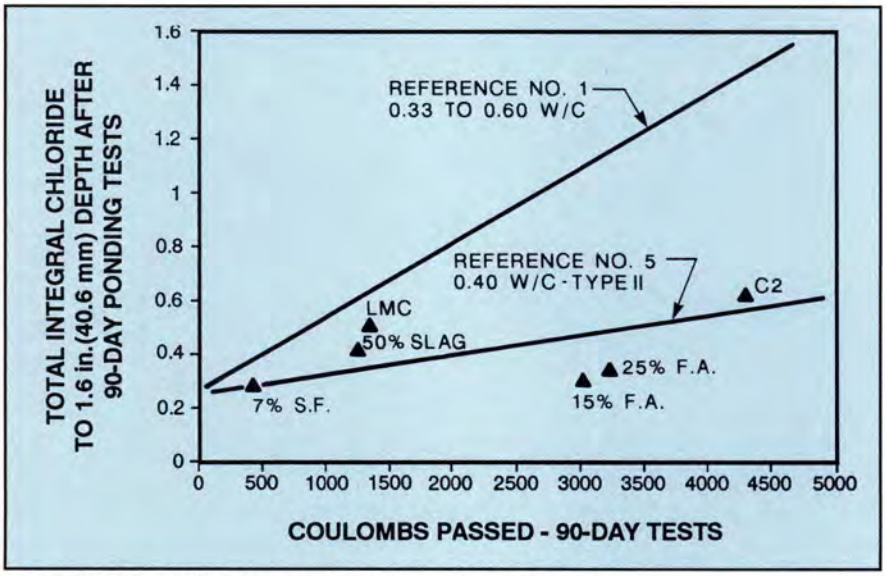

Fig. 4. ASTM C1202 correlation data from Refs. 1 and 5.

ASTM C1202 Reference 4 — Protection Against Chloride-Induced Corrosion[7]

This 1988 paper does not contain results from 90-day ponding tests; therefore, correlation between "coulombs passed" and "90-day ponding chloride ion contents" cannot be made or discussed.

ASTM C1202 Reference 5 — Use of Admixtures to Attain Low Permeability Concretes[8]

This 1988 paper contained data on 0.40 water-cement ratio concretes. The concretes were manufactured with portland cement, 15 and 25 percent replacement of cement with Class F fly ash, 50 percent replacement of cement with slag, and 7 percent replacement of cement with silica fume. A 0.37 water-cement ratio LMC was also tested in accordance with the AASHTO T277 and T259 methods. Tests were made on duplicate specimens, using Types I and II cement with these six mixtures. These air-entrained concretes were moist-cured for 14 days, then air-dried for 14 days. The AASHTO T259 ponding tests commenced 28 days after casting. The coulomb values were measured 28, 90 and 365 days after casting.

The *I* levels were not reported in the paper, but chloride values determined at various depths were reported. We calculated the *I* values based upon the reported average chloride ion contents at two depths. These *I* values were used to construct Fig. 4, for the Type II cement concretes (C2). The coulomb values for the 90-day concretes were always greater than the 28-day values, which is the reverse of what may be expected. The 365-day coulomb values were, in many cases, also greater than the 90-day values; however, the silica fume and LMC coulomb values were lower.

The data shown in Fig. 4 for these six different mixtures do not correlate with the ASTM C1202 Ref. 1[4] 0.40

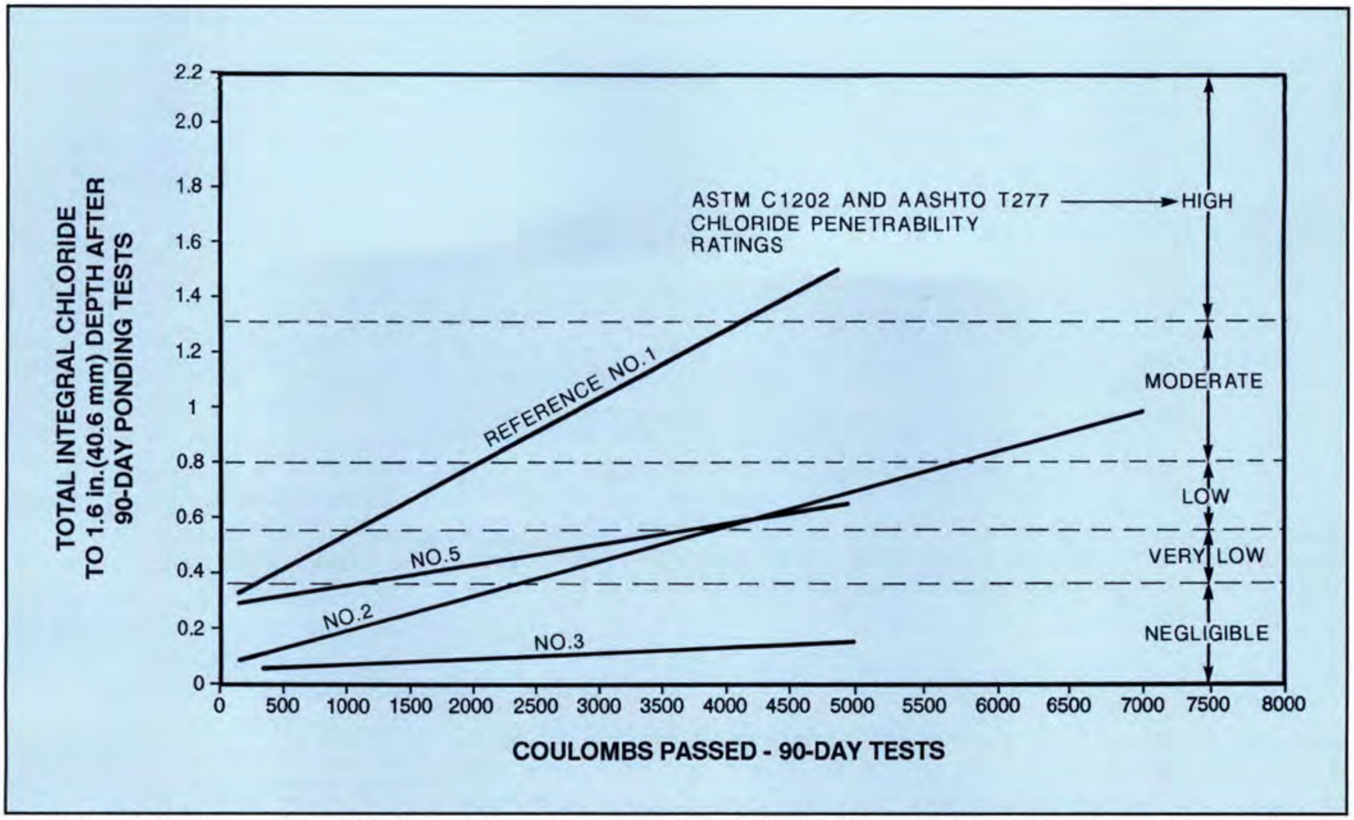

Fig. 5. ASTM C1202 correlation data from Refs. 1, 2, 3 and 5 as related to ASTM and AASHTO chloride penetrability ratings (based on Ref. 1 total integral chloride).

water-cement ratio concrete. However, the LMC data from ASTM C1202 Refs. 1 and 5 correlate well, with 800 to 1300 coulombs passed and *I* values of about 0.5 to 0.6. The 15 percent fly ash C2 concrete and the silica fume C2 concrete have about the same *I* values, yet the fly ash concrete had a coulombs value of about 3000, which is 6½ times the silica fume value. The 15 and 25 percent fly ash C2 concretes had significantly lower *I* values than the LMC concrete, yet their coulombs values were about 2.5 times the LMC values. The Ref. 5 researchers noted that a precise correlation between the test methods was not attained, although a general relationship was observed.

Correlations from ASTM C1202 References 1, 2, 3 and 5

A summary of the correlation between the six-hour rapid test method and the 90-day ponding test method is shown in Fig. 5 for the four ASTM C1202 references containing rapid test and 90-day data. Fig. 5 and Table 2 show the relationship between "coulombs passed" and the actual "chloride penetrability" ratings, varying from "high" to "negligible" based upon "total integral chloride" as reported in ASTM C1202 Ref. 1[4] and Table 1.

These ratings in Fig. 5 and Table 2 show wide variance and a lack of correlation between coulombs passed and 90-day ponding tests. The original arbitrary classification scale cited in Ref. 1, and now shown in ASTM C1202, is inappropriate and should not be used. Prior to specifying materials based on ASTM C1202 test results, correlations to long-term tests must be found.

Silica-Fume Modified Concrete Correlation Data

ASTM C1202 Refs. 2, 3 and 5 contained limited data on silica-fume modified concrete and companion conventional concrete tested by both methods. The benefits of silica fume admixtures are well recognized; however, ASTM C1202 overestimates the magnitude of improvements derived from such admixtures. Fig. 6 shows typical data and relationships between "coulombs passed" and "total integral chloride" for the ASTM C1202 Refs. 2, 3 and 5 concretes. The conventional concretes had water-cement ratios of 0.29 to 0.40 prior to the addition of silica fume, and other concretes utilized 13, 15 and 7 percent fume. The resultant water to cementitious ratios ranged from 0.26 to 0.40 for the fume modified concretes.

Table 2. Rating of chloride penetrability based on T259 and T277 results presented in Fig. 5.

Coulombs	Reference 1	Reference 2	Reference 3	Reference 5
5000	High	Low	Negligible	Low
2500	Moderate	Very low	Negligible	Very low
1500	Low	Very low	Negligible	Very low
500	Very low	Negligible	Negligible	Very low
<100	Negligible	Negligible	Negligible	Negligible

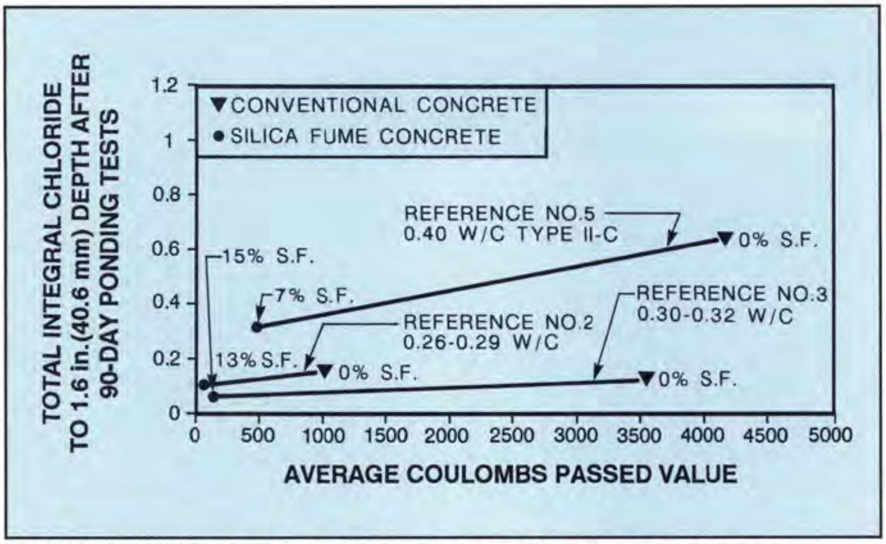

Fig. 6. Relationship of average "coulombs passed" values and total integral chloride values for concrete with and without silica fume additions (from Refs. 2, 3 and 5).

The following observations can be made from Fig. 6:

- The addition of these particular dosages of silica fume to low water-cement ratio concrete produces a very large decrease in "coulombs passed" values. The accompanying reductions in *I* values are much smaller.
- The three conventional concretes had coulomb values ranging from 850 to 4200, averaging at about 2600. When modified by the silica fume additions, the coulomb levels ranged from 44 to 490, averaging at 260. These average data indicate that the conventional concrete coulomb value was 10 times the silica-fume modified concrete coulomb value.
- The three conventional concretes had *I* values ranging from 0.16 to 0.62, averaging at about 0.27. The same concretes with the silica fume additions had *I* values ranging from 0.05 to 0.31, with an average of 0.14. The *I* values for the conventional concrete averaged at about 1.8 times those for the silica fume concrete.
- A higher, 0.40 water-cement ratio concrete with 7 percent silica fume and a coulomb value of only 500 can have a much higher *I* value than conventional HRWR concretes with 0.30 to 0.32 water-cement ratios, which had coulombs passed values from 1000 to 5000.

Research reported in Ref. 5 of ASTM C1202[8] contained data on 0.40 water-cement ratio concrete with and without 7 percent silica fume. While previous discussions in this paper have concerned the *I* value, this discussion relates only to the chloride ingress to the ¾ to 1¼ in. (19 to 32 mm) depth, the region where reinforcing bars have commonly been specified in bridge decks and parking structures. These tests were on concrete containing two cements, a Type I (C1) and a Type II (C2). The relevant data for the C1 and C2 concrete are listed in Table 3.

Table 3. Chloride content and coulombs passed for C1 and C2 concretes.

Concrete type	Coulombs passed (90 days)	Acid-soluble chloride content at ¾ to 1¼ in. after 90-day ponding,* percent by weight of concrete
Conventional concrete C1	3590	0.26
7 percent silica-fume modified concrete C1	490	0.17
Conventional concrete C2	4210	0.38
7 percent silica-fume modified concrete C2	460	0.31

* Corrected for baseline chloride.
Note: 1 in. = 25.4 mm.

These data show that the conventional 0.40 water-cement ratio concrete coulomb value is seven to nine times that for silica fume concrete. However, the conventional concrete chloride content at the ¾ to 1¼ in. (19 to 32 mm) level is only 1.2 to 1.5 times the chloride content in the silica fume concrete.

None of these fume modified concrete studies utilized water-cement ratios higher than 0.40 during AASHTO T259 ponding tests. The data in Fig. 6 suggest that concretes with higher water-cement ratios (0.45 to 0.55) could be made with silica fume ingredients and produce spuriously low "coulombs passed" values of less than 1000 coulombs. High water-cement ratio conventional concretes might easily produce 4000 to 6000 coulomb values without silica fume, as shown in Fig. 2, but the values could easily be reduced to 400 to 1000 with silica fume.

The *I* values for these higher water-cement ratio silica fume concretes could still be high, possibly at levels of 0.30 to 0.45. Therefore, correlation of the ASTM C1202 test to long-term ponding tests is especially needed before accepting silica-fume modified concretes with moderate or high water-cement ratios.

During the literature review, examples of concern about high water-cement ratio concrete producing low coulombs were found. A recent paper[10] presented "coulomb passed" data on a 0.70 water-cement ratio conventional and slag concrete. As with most reviewed papers, there were no 90-day ponding tests presented, and there were no correlations of "coulombs passed" data to actual chloride penetration into ponded concrete test slabs. The concrete properties are listed in Table 4.

This very high water-cement ratio, low compressive strength slag cement concrete, with an aggregate to cementitious ratio of nearly 10 to 1, produced a 28-day coulomb value of 718. An essentially identical 0.70 water-cement conventional concrete with no slag cement substitution produced a 28-day coulomb value of 7366. These data show that the substitution of 50 percent slag cement reduced the coulomb value by a factor of 10. This same study contained data for 0.55

and 0.45 water-cement ratio concretes that showed that a 50 percent substitution of slag cement for portland cement resulted in a reduction of the 28-day coulombs by factors of 7.7 and 6.0, respectively.

While this research suggests that a 0.70 water-cement ratio concrete with a 28-day strength of 1300 to 2200 psi (8.7 to 14.8 MPa) should be classified as having a "very low" chloride penetrability, based upon the 718 coulomb value, we believe the data illustrate that the rapid chloride permeability test can error in favor of poor quality concrete under a number of circumstances.

Of great concern is the potential of elimination during the specification and bidding processes of low water-cement ratio conventional concretes having water-cement ratios of 0.30 to 0.40, which produce "very low" to "negligible" *I* values during 90-day ponding tests, as shown in Table 2, yet which cannot achieve the 700 to 1000 coulomb values commonly specified. These conventional concretes, with coulomb values of 1500 to 4000, produced lower chloride penetrability in the AASHTO T259 studies than the 0.40 water-cement ratio C2 silica fume concrete of Ref. 5, which had a 90-day coulomb value of 460. These data suggest that construction projects recently built with concrete containing higher water-cement ratios with silica fume or slag cement, but low coulomb values, may not be as impervious to chloride as the engineers and owners desire.

Other researchers have also commented indirectly on these concerns. Berke, Dallaire and Hicks[11] commented:

> . . . even in a concrete with an initial AASHTO T277 rapid chloride permeability of 348 coulombs, substantial chloride has reached the reinforcement after five years of exposure. This 7.5 percent silica fume mix at 0.48 water-cement, or 0.45 w/(C+SF), was also beginning to severely corrode at five years of exposure. The resistivity of this concrete is over 40,000 ohm-cm; thus, high resistivities do not guarantee the elimination of corrosion.

A paper by Berke, Scali, Regan and Shen[12] contains similar observations.

Table 4. Concrete properties for slag concrete and conventional concrete.

Concrete properties	Slag blend	Conventional concrete
Cement content, lbs/yd^3 (kg/m^3)	169 (100)	340 (200)
Slag cement content, lbs/yd^3 (kg/m^3)	169 (100)	—
Water content, lbs/yd^3 (kg/m^3)	238 (141)	238 (141)
Aggregate content, lbs/yd^3 (kg/m^3)	3258 (1932)	3258 (1932)
28-day compressive strength, psi* (MPa)	1300 to 2260 (8.9 to 15.5)	1840 to 2900 (12.6 to 19.9)
Coulombs passed	718	7366

* After 3 to 28 days of moist cure.

> Low rapid chloride permeability readings (<1000 coulombs) and high resistivities are indicators of good corrosion performance. However, moderately high permeability readings (1000 to 4000 coulombs) and low resistivities are not necessarily an indication of poor corrosion performance.

A 1992 paper, "A History of the Rapid Chloride Permeability Test," by Whiting and Mitchell[9] contains five general observations and cautions:

1. The final group, polymer-impregnated and polymer concrete, show negligible permeability to chlorides.

2. It (the laboratory test method) 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 "fall-back" position, it was not developed and tested nearly as thoroughly as the field method, and no systematic investigations were carried out regarding the many variables that might influence the test.

3. This version of the test method included a table to "interpret" the results; it is reproduced here as Table 1. 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 1 may be used as estimates until more data have been developed by a number of agencies on a wider range of concretes. While further testing of some of these variables has since been carried out, this has been very limited, and the values in Table 1 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.

4. The availability of commercial instrumentation designed specifically to conduct AASHTO T277/ASTM C1202 now makes it possible for almost any test lab to obtain a "permeability" value. A word of caution is advised, however, as the quantity measured by the rapid chloride ion permeability test (RCPT) is not permeability in the strictest sense, but an indication of permeability based on the ability of a given concrete specimen to conduct electric current. Any materials which cause concrete to be more (or less) conductive will increase (or decrease) the value obtained during the RCPT, regardless of the effects which such materials or treatments have on actual permeability, diffusion or other mass transport phenomena.

5. Acceptance is based on the average value of charge being less than the specified limit. Statistically based acceptance schemes are non-existent. In the authors' opinion, further work on the definition of acceptable limits, on development of statistical acceptance schemes, and on 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 aspects of construction — such as degree of consolidation and type and extent of curing.

The first statement on polymer-impregnated and polymer concrete is potentially misleading. While the PIC and PC concretes had essentially zero coulomb values, due to their non-conducting electrical properties, both showed significant I values of 0.16 to 0.34 following the 90-day ponding test. In addition, the high electrical resistivity values for polymer-modified, silica fume-modified and blast furnace slag-modified concretes mask their real chloride ion ingress properties.

A paper by Andrade,[13] published in 1993, reviews the movement of ions during the AASHTO T277 test. It was shown that the measured charge passed is more a function of the movement of hydroxyl ions in the concrete than the movement of chloride ions. Pozzolans will react with hydroxides, and this may explain why concretes containing pozzolanic materials, such as silica fume and slag cements, exhibit much lower charge passed values. Andrade concludes, "The rapid chloride permeability test (AASHTO) in its present formulation cannot inform on concrete permeability to chlorides."

A presentation and paper by Arup, Sorensen, Frederiksen and Thaulow[14] at the 1993 NACE Corrosion/93 meeting reviews the rapid chloride ion permeability test. Numerous questions were raised. These authors concluded:

- The information provided by a RCPT or an AASHTO test is — at the most — equivalent to that which can be obtained by measuring the resistivity of the water-saturated sample.
- Neither the RCPT nor the resistivity measurement can be taken as a measure of the diffusion resistance of the concrete, unless the conductivity of the porewater in that particular type of concrete and in that particular hydration state is known and the appropriate correction made.
- The results obtained in the RCPT cannot be used to calculate the diffusion coefficient (D) for chloride in concrete and will therefore not allow predictions of chloride penetration with time.

CONCLUSIONS AND RECOMMENDATIONS

Reliable and proper correlations do not exist between the six-hour rapid chloride permeability test results and the 90-day ponding test results when different studies are compared. This lack of correlation is based upon numerous factors that are briefly discussed in this paper and more extensively discussed in other recent papers.[13,14]

The rapid test was never intended as a predictor of the quantitative amount of chloride that would penetrate into any given concrete. Those specifiers who are using the rapid test method for this purpose are at fault. As stated in ASTM C1202, the rapid test should not be used unless proper correlations are made with long-term ponding tests.

Use of the rapid electrical test method to specify silica fume-modified and other pozzolantically modified concrete, with their naturally high electrical resistivity, is premature. Adequate correlations, as required in ASTM C1202, between the rapid electrical test method and 90-day ponding tests do not exist for these concretes. Of great concern is the specification and use of higher water-cement ratio concretes when based solely on the low coulombs passed value.

Conventional concretes made with only portland cement may have coulomb values of 6 to 15 times higher than the same mixture with silica fume or slag cement. Much of this difference is due to the inherent high electrical resistivity of these modified concretes. Typical conventional concrete may have a 5- to 10-fold decrease in coulombs passed when 7 percent silica fume is added, while the actual chloride ingress after 90-day ponding tests may decrease only one to two times.

Chloride penetrability into concrete is dominated by the concrete water-cement ratio, with additional benefits when silica fume, fly ash, latex and slag additions are used. The studies reviewed show that virtually impermeable conventional concretes can be produced with very low water-cement ratios of 0.30 to 0.32, even though their coulomb values may range from 1000 to 5000. These data indicate that, during project bidding phases or during construction, the elimination of concretes with coulomb values of higher than 700 to 1000 based solely on ASTM C1202 is not appropriate.

While further research regarding the general subject of chloride penetration of concrete is beneficial, it is essential in the case of the rapid chloride test. The concerns of ASTM C1202 regarding the correlation of the rapid chloride test and the 90-day ponding test for silica fume concrete have not been met adequately, making this application of the rapid chloride test highly questionable. Material selection for the design of low permeability concrete should be based on 90-day or longer ponding tests (AASHTO T259) and not ASTM C1202.

Engineers continue to require rapid chloride tests of silica fume concrete, sometimes on a scale approaching that of routine jobsite quality control testing. Such indiscriminate use of the rapid chloride test — without development of initial correlation data on specific concretes — should be stopped.

Table 1 in the ASTM C1202 specification should be removed because this "classification" system based upon coulombs passed values is incorrect and is not the intent originally proposed by the designers of the test procedure.

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