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Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results

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Abstract

The rapid chloride permeability test (RCPT)—American Society of Testing and Materials (ASTM) test method C1202 or American Association of States Highway and Transportation Officials (AASHTO) test method T277—is virtually a measurement of electrical conductivity of concrete, which depends on both the pore structure characteristics and pore solution chemistry of concrete. This paper discusses the effects of several factors, such as cement composition, replacement of cement with supplementary cementing materials and inclusion of aggregate, on the electrical conductivity or RCPT results of hardened cement mortars and concrete. Analyses based on published results have indicated that all the three factors may have significant effects on the chemistry and specific conductivity of concrete pore solution, which has little to do with the transport of ions in the solution. Thus, RCPT is not a valid test for evaluation of permeability of concretes made with different materials or different proportions.

Keywords: Chloride permeability; Electrical conductivity; Pore solution; Aggregate; Fly ash; Slag; Silica fume

1. Introduction

The rapid chloride permeability test (RCPT)-ASTM C1202 [1] or ASSHTO T277 [2] has been criticized by many scientists and researchers all over the world during the past decade because of its lack of scientific bases and harsh testing conditions [3–10]. These standards specify the rating of chloride permeability of concrete based on the charge passed through the specimen during 6 h of testing period. ASTM C1202 recognizes that a correlation between the rapid chloride permeability test and the 90-day ponding test results is necessary, while AASHTO T277 does not require this correlation. A comparison has indicated that conventional concretes made with only Portland cement may exhibit coulomb values 6 to 15 times higher, but that the corresponding actual chloride ingress in the 90-day ponding test is only 1 to 2 times higher than the same concrete mixtures but with silica fume [6]. Another study has also found that the general correlation between chloride ingress and coulomb values given in the AASHTO T277 or ASTM C1202 test procedures appears invalid for use with concretes containing silica fume, fly ash and high-range water-reducing admixtures [11].

Recently, several discussions have been published regarding the validity of the test method [12,13]. The effects on the concentration of conductive ions and the RCPT results from the use of $Ca(NO_3)_2$ in concrete are acknowledged. However, the effect of other materials on pore solution chemistry and how the pore solution chemistry affects the RCPT results are not mentioned at all.

Dry concrete is a semiconductor or insulator. Electrical conductivity of water saturated concrete depends on not only the pore structure and but also the chemistry of pore solution. The transport of chloride ions has little to do with the chemistry of pore solutions, but many factors such as cement composition, aggregate, concrete mixing proportions, use of supplementary cementing materials, chemical additives, etc. can have very significant effects on the concentration of conductive ions in the pore solution. RCPT has been used to evaluate the chloride permeability of hardened cement mortars and concretes made with special cements or supple-

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mentary cementing materials [14–24]. It is obvious that the use of RCPT in some of those studies has resulted in some invalid or misleading conclusions. In one study [16], it was found that the inclusion of sands or Class F fly ash decreases chloride permeability significantly, while their effects on water permeability are much smaller. In another study [21], a replacement of 10% cement with class F fly ash can even significantly reduce the chloride permeability of cement mortars at 7 days. Shi [22] used RCPT to test Portland cement and three alkali-activated slag mortars and found that although sodium silicate activated slag cement mortar showed the lowest pore porosity and water permeability among the four cement mortars, it gave much higher passed coulombs than the other three mortars due to the high concentration of conductive ion concentration in the pore solution. In the most recent publication [24], it is found that the RCPT results from the same concrete specimens do not relate directly to the three water-to-cementing material ratios (0.38, 0.45 and 0.52) used, and some concrete specimens with lower water-to-cementing material ratio showed high RCPT values. On other hand, it can be expected that the concrete with a water-to-cement ratio of 0.38 should have a much lower permeability than the concrete with a water-to-cement ratio of 0.52.

This paper has used published results to show how several factors such as cement composition, inclusion of aggregate and use of supplementary cementing materials affect the pore solution chemistry, the electrical conductivity of the pore solution and the RCPT results. The objective of this paper was to further analyze the validity of the RCPT method for evaluation of concrete made with different materials or different proportions.

2. Specific electrical conductivity of concrete pore solution

For a strong electrolyte, its equivalent conductivity λ_i decreases with the square root of equivalent concentration C_i [25]:

$$\lambda_i = \lambda_{i,0} - (0,2289\lambda_{i,0} + 60.19)\sqrt{C_i} \qquad (1)$$

where $\lambda_{i,0}$ is the equivalent conductivity at infinite concentration. Table 1 lists the equivalent conductivity of aqueous ions commonly identified in concrete pore solution.

For a given temperature, the specific conductivity of a solution can be expressed as follows [26]:

$$\rho = \rho_{water} + \Sigma C_i \lambda_i / 1000 \qquad (2)$$

where ρ = specific electrical conductivity of aqueous solution ($m^{-1}\ \Omega^{-1}$); ρ_{water} = specific electrical conductivity of water (= $10^{-5}\ m^{-1}\ \Omega^{-1}$); C_i = equivalent electrical concentration of ion I (equiv m^{-3}); and λ_i = equivalent electrical conductivity of ion I (m^2.equiv$^{-1}\ \Omega^{-1}$).

Eq. (1) is well obeyed to a concentration of about 0.1 M aqueous univalent ions, only slight deviations are observed for NaOH or KOH solutions up to a concentration of 1 M [25].

Appreciable concentrations of Na^+, K^+, OH^-, Ca^{2+} and $SO_4{}^{2-}$ from the cement components enter into the mixing water during concrete mixing. After setting and early hydration, the Ca^{2+} and $SO_4{}^{2-}$ diminish to negligible values, leaving a solution composed essentially of dissolved alkali hydroxides. In most cases, the concentration of alkali hydroxides in concrete pore solution is less than 1 M. Thus, the specific electrical conductivity of concrete pore solution can be calculated with satisfactory accuracy based on the concentrations of OH^-, Na^+ and K^+ using Eqs. (1) and (2).

2.1. Effect of supplementary cementing materials on specific electrical conductivity of concrete pore solution

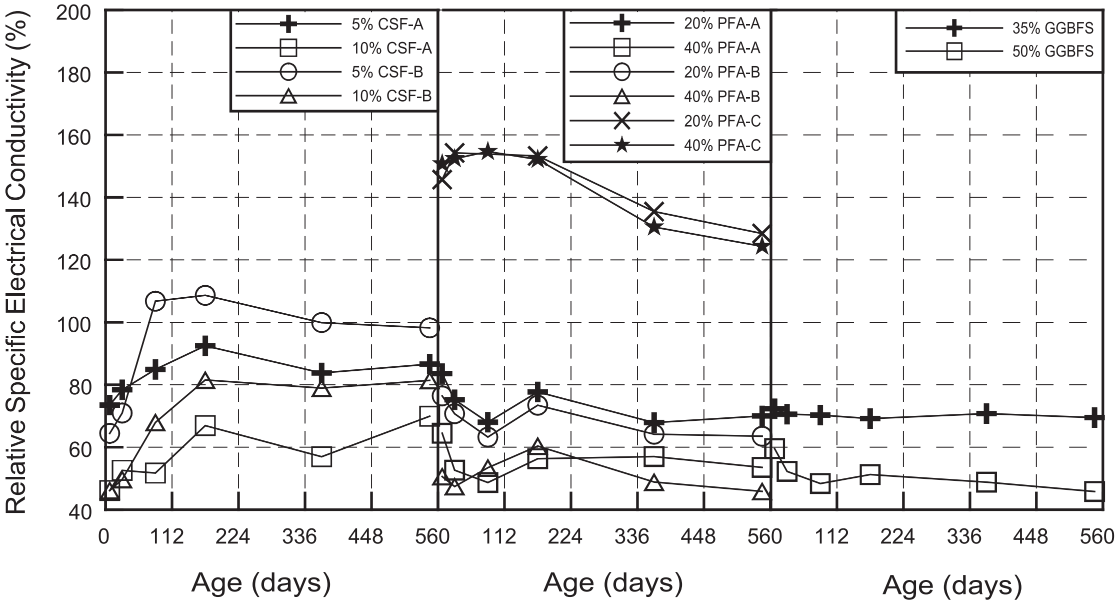
The use of supplementary cementing materials such as ground blast furnace slag, silica fume, metakaoline, coal fly ash and natural pozzolan can have a very significant effect on the pore solution chemistry of concrete, depending on the dosage and composition of these supplementary cementing materials [27–35]. Supplementary cementing materials with low alkali content will incorporate more alkalis into hydration products than they release to the pore solution, which results in a lower alkali concentration or lower pH value in the pore solution [33]. This is the basis for the use of those supplementary cementing materials to decrease the alkalinity of pore solution in concrete materials down to a safe level to suppress alkali–aggregate expansion of concrete.

In a previous work [10], Shi and coworkers calculated how supplementary cementing materials affect the electrical conductivity of pore solution or the RCPT results using results published by Wiens et al. [34]. In this paper, three sources of results published by Duchesne and Berube [33], Sheata et al. [35] and Page and Vennesland [28] are used to demonstrate the effects of different supplementary cementing materials on electrical conductivity of pore solution. Figs. 1–3 show the calculated specific electrical conductivity of pore solutions. Results in Figs. 1 and 2 are based on the concentrations of OH^-, Na^+, and K^+ in pore solutions, and results in Fig. 3 include concentrations of OH^-, Na^+, K^+, $SO_4{}^{2-}$, Cl^- and Ca^{2+} in pore solution.

Fig. 1 plots the relative specific conductivities of pore solution of cement pastes containing two condensed silica

Table 1
Equivalent conductivity of aqueous ions at infinite concentration at 25 °C [25]

Ion	Na^+	K^+	Ca^{2+}	$SO_4{}^{2-}$	OH^-	Cl^-
Equivalent conductivity λ_0 (m^2 equiv$^{-1}\ \Omega^{-1}$)	0.00501	0.00735	0.00595	0.00798	0.0198	0.00763

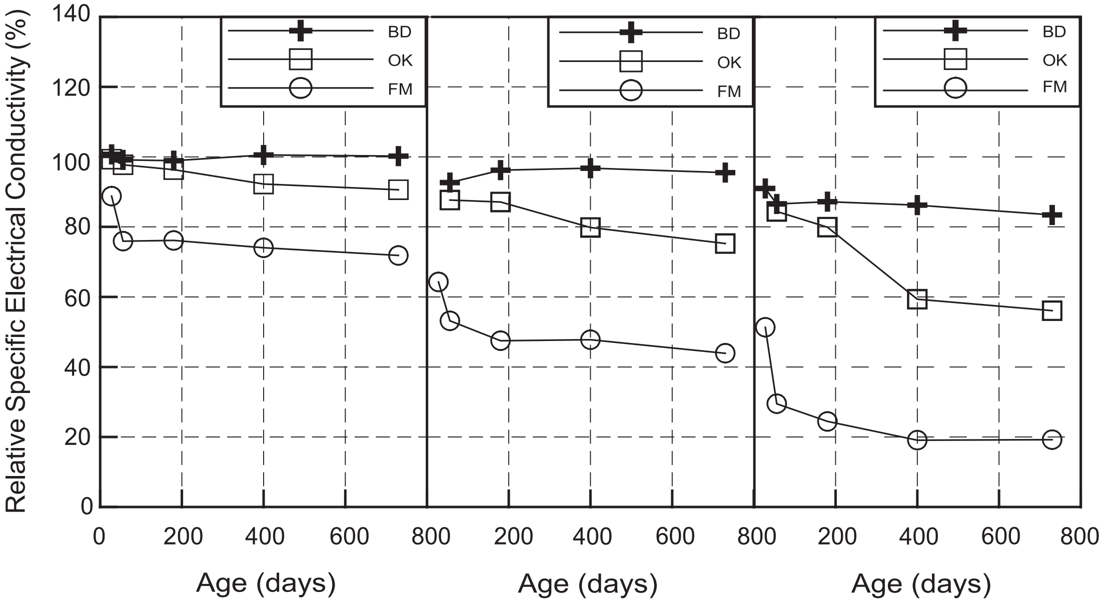


(a) With Silica Fume (b) With Fly Ash (c) With Blast Furnace Slag

Fig. 1. Effect of supplementary cementing materials on specific electrical conductivity of pore solution of hardened cement pastes relative to pure Portland cement pastes (calculated based on results from Ref. [33]).

fumes (CSF-A and CSF-B), three coal fly ashes (PFA-A, PFA-B and PFA-C) and one blast furnace slag relative to that of pure cement pastes. A replacement of 5% Portland cement with CSF-A decreases the specific electrical conductivity of pore solution to approximately 75% of that of Portland cement pastes at 7 days. However, it increases with time and reaches more than 90% of the conductivity of Portland cement pastes at 183 days, and decreases slightly thereafter. When the replacement is increased to 10%, the relative specific conductivity of pore solution is only about 45% at 7 days and reaches approximately 60% at 183 days.

CSF-B behaves differently from CSF-A. Although a replacement of 5% Portland cement with CSF-B decreases



(a) 25% Fly Ash (b) 50% Fly Ash (c) 75% Fly Ash

Fig. 2. Effect of fly ash on specific electrical conductivity of pore solution of hardened cement pastes relative to pure Portland cement pastes (calculated based on data from Ref. [35]).

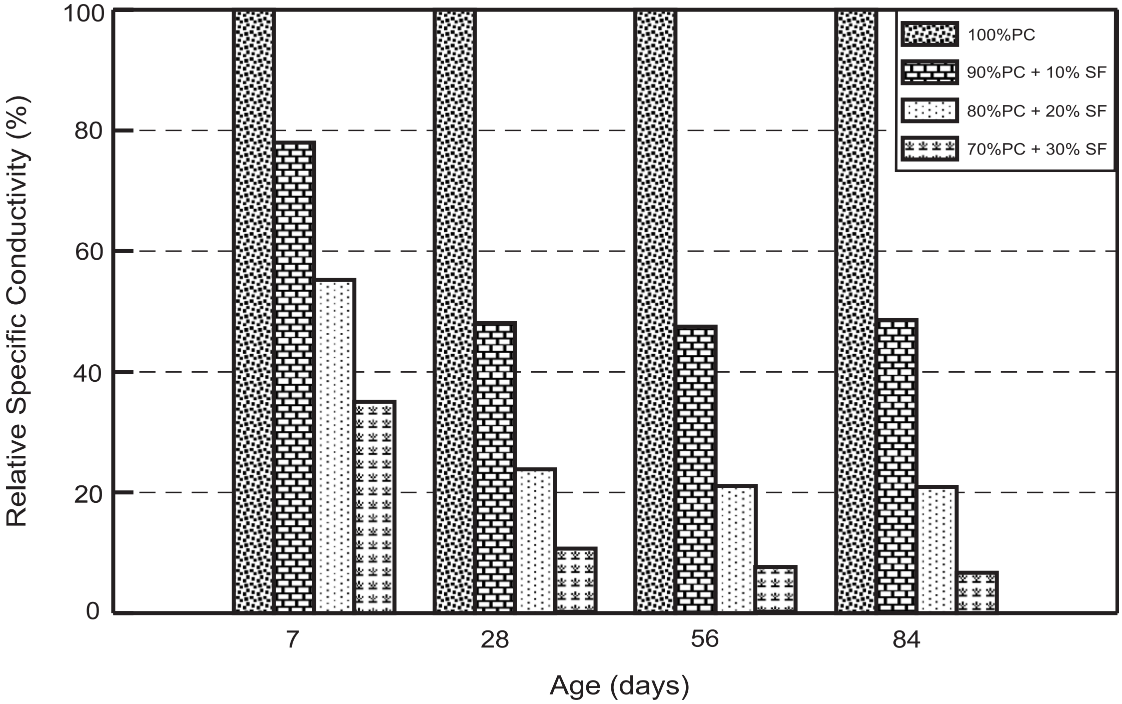


Fig. 3. Effect of silica fume content on relative specific conductivity of cement pastes at different ages (calculated based on data from Ref. [28]).

the relative specific conductivity to below 70% at 28 days, it increases to over 100% at 90 and 183 days and remains at about 100% at 365 and 540 days. This means that the replacement of 5% Portland cement with CSF-B decreases the specific conductivity of pore solution before 90 days, and increases or does not affect it after 90 days.

PFA-A and PFA-B behave very similarly. A replacement of 20% cement with PFA-A or PFA-B decreases the specific conductivity of pore solution by approximately 20% to 25% at 28 days, and approximately 30% to 40% at 550 days, while 40% replacement decreases the alkali concentration in pore solution by approximately 35% before 28 days and approximately 40% to 50% after 28 days. However, A replacement of 20% or 40% of cement with PFA-C shows almost the same effect and increases the specific conductivity of pore solution around 50% at 183 days and then decreases with time thereafter.

A replacement of 35% cement with GBFS decreases the relative specific conductivity of the pore solution to approximately 70% regardless of the age. When the replacement increases to 50%, it decreases the relative specific electric conductivity to 60% at 7 days and approximately 50% after 90 days.

The results in Fig. 2 indicate that the effects of fly ash replacement on the specific conductivity of pore solution vary with fly ash sources, replacement levels and ages. At 25% replacement level, fly ash BD increases the specific electrical conductivity of pore solution at all the times, fly ash OK decreases the relative specific electrical conductivity of pore solution from approximately 100% at 28 days to approximately 83% at 730 days, and fly ash FM decreases it to approximately 83% at 28 days, 64% at 90 days and then it decreases slightly with time thereafter.

As the fly ash replacement level increases to 50% and 75%, the specific electrical conductivity of pore solution decreases with fly ash replacement level. Fly ash BD always shows the highest and FM always shows the lowest electrical conductivity of pore solution.

Fig. 3 shows the effect of silica fume content on specific conductivity of pore solution of hardened cement pastes. The replacement of 10% cement by silica fume can reduce the specific conductivity of cement pastes by approximately 22% at 7 days and approximately 52% at 28 days of hydration. As the silica fume content increases, the specific conductivity of pore solution decreases. The use of 30% silica fume can reduce the specific conductivity of cement pastes by approximately 63% at 7 days and approximately 90% at 28 days of hydration. The effect of silica fume on specific conductivity of pore solution does not change with time after 28 days. The effect of silica fume on the RCPT results from those pastes should be the same as that on the specific conductivity of cement pastes as described above.

2.2. Effect of alkali content in cement on electrical conductivity of concrete pore solution

Portland cement contains an amount of alkalis that depend on the raw materials and production process used. Gebhardt [36] conducted a survey on characteristics of

North American Portland cements in 1994. Alkali contents of nine types of Portland cement are summarized in Table 2. LA means low alkali cements. The average alkali contents of normal ASTM Type I, II and III cements are between 0.91% to 0.94%, while the average alkali contents of low alkali ASTM Type I, II and III vary from 0.43% to 0.45%. Cement can release almost all its alkalis to the pore solution and the pore solution of concrete consists mainly of alkali hydroxides after 28 days of hydration [32,37]. This means that if two concretes, one made with normal and one with low alkali cements, have the exact same pore structure, the electrical conductivity, or the RCPT results, of concrete made with low alkali cement, on average, will be less than that of the one made with normal cement. The results in Table 2 also indicate that the lowest alkali content of Portland cement is only 0.05%, while the highest alkali content is 1.2%. Thus, alkali concentrations in pore solution of concretes made with cements containing very low alkali content and very high alkali content can be very different, which in turn can have a very significant effect on the electrical conductivity of pore solution or the RCPT results of concrete.

2.3. Effect of aggregate on electrical conductivity of concrete

Aggregate usually does not release noticeable amount of ions into pore solution of concrete. However, some conductive ions may be extracted from aggregates into pore solution. Grattan-Bellew [38] has reported that significant amount of alkalis are extracted from limestone aggregate into the pore solution of concrete, which will have a significant effect on the electrical conductivity or the RCPT results of concrete.

The other important factor is the effect of volume of aggregate portion on electrical conductivity of concrete. Measurement of electrical conductivity of concrete has been used to characterise features and formation process in the transition zone in Portland cement concrete [39–41] made with limestone and quartz sands. The electrical conductivity of concrete specimen $\sigma(t)$ at hydration time t is inversely proportional to the volume fraction of aggregate in concrete as follows [40]:

$$\left.\begin{aligned}
&\sigma(t) = k(t)\varphi_a + b(t)\\
&k(t) = 3\left(\frac{\delta}{r}\right)\left(1+\frac{\delta}{2r}\right)[\sigma_f(t)-\sigma_p(t)] - \frac{3}{2}\sigma_p(t)\\
&b(t) = \sigma_p(t)
\end{aligned}\right\} \quad (3)$$

where φ_a = volumetric fraction of aggregate in concrete, δ = thickness of the interfacial zone between cement paste and aggregate, r = average radius of aggregate, $\sigma_f(t)$ = conductivity of the interfacial zone between cement paste and aggregate at time t, and $\sigma_p(t)$ = conductivity of cement paste at time t.

Based on Eq. (3), the passed coulombs of mortar or concrete will decrease with the inclusion of sands or limestone aggregate for a given water-to-cement ratio.

If the aggregate introduced is more permeable than cement pastes, it will definitely increase the chloride permeability of the concrete [42]. However, for a given water-to-cement ratio and hydration degree of cement, water permeability of concrete made with low-permeability aggregates is about one to two orders lower than that of cement pastes due to the interfacial effect between aggregate and cement paste [43]. One recent study [44] based on the measurement of total chloride distribution concluded that the aggregate had a dilution effect on chloride ingress, but no major effects from the interfacial transition zone and pathway tortuosity occur. However, several studies have concluded that the introduction of aggregate increases the diffusivity of chlorides mainly because of the interface effect [45–48]. It was found that the diffusivity of chloride in the interfacial transition zone is 10 times greater than that in bulk cement paste [45]. For the same degree of hydration, introduction of sand particles results in higher chloride transportation coefficients [46]. Another two laboratory studies [47,48] noticed that the chloride diffusion coefficient showed little change with aggregate content when the aggregate content was less than 30% by volume, but it increased significantly with the increase of aggregate content when the aggregate content was greater than 30% by volume (Fig. 4).

Roy et al. [16] studied the effect of inclusion of sands on water permeability, RCPT results and pore size distribution and porosity of hardened cement pastes and mortars cured at 23 and 38 °C for a given water-to-cement ratio of 0.53. When the addition of sands increases the volume of the material system by approximately 139%, the porosities are increased by approximately 121% (37.1% for pastes and 16.8% for mortars) when cured at 23 °C and approximately 79% (35.4% for pastes and 19.8% for mortars) when cured at 38 °C. This means that the addition of sand does increase

Table 2
Summary of alkali contents in different types of North American Portland cement (%)

Cement type	No. of cement sample	Na_2O (equiv)		
		Min	Max	Average
I	18	0.62	1.20	0.91
I LA	37	0.11	0.58	0.43
II	8	0.81	1.12	0.94
II LA	98	0.05	0.60	0.45
III	13	0.82	1.20	0.94
III LA	26	0.17	0.59	0.43
IV and IV LA	4	0.29	0.42	0.36
V	4	0.69	0.76	0.71
V LA	31	0.24	0.59	0.48

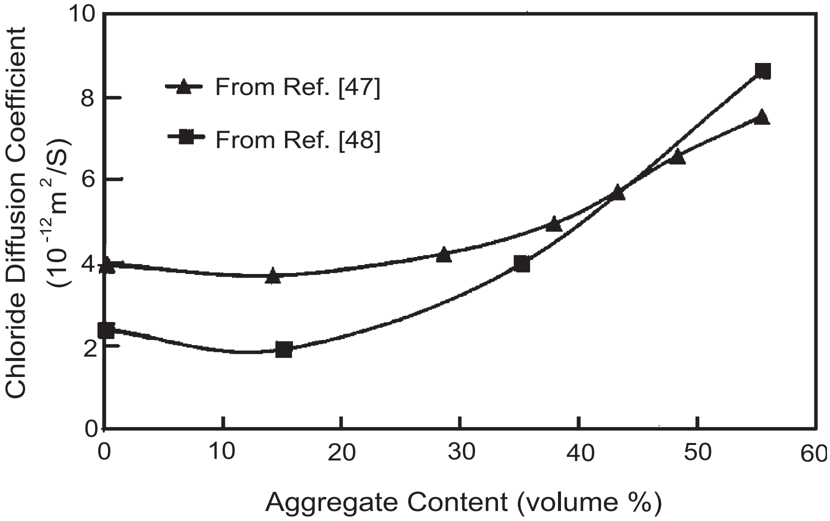


Fig. 4. Effect of aggregate content on chloride diffusion coefficient [47,48].

the porosity of cement paste. It is found that during the RCPT, the electrical current through hardened pastes was too high to complete the test on the samples, while mortar samples had passed a charge of 2999 C (coulombs) for samples cured at 23 °C and 2279 C for samples cured at 38 °C. Although the total porosities of paste samples were higher than that of mortar samples, the water permeability of mortars is two orders higher than that of the pastes cured at 23 °C and slightly lower than that of the pastes cured at 38 °C. There is no doubt that there are differences between the transport mechanisms for water and Cl^-. However, the following two factors may have played an important role for decreasing the RCPT results or the electrical conductivity of cement mortars: (1) the addition of sands increases the porosity in the cement pastes and dilutes the concentration of conductive ions in the pore solution; (2) alkalis can be adsorbed on the surface of acidic aggregate such as sands and may not be as mobile as those in the bulk pore solution. It has been reported that alkalis concentrate around both alkali-reactive aggregate and nonreactive aggregates [49,50]. Thus, the change in RCPT results or electrical conductivity due to the inclusion of aggregates does not really reflect its effects on the permeability of the material system.

3. Rating criteria

ASTM C1202 [1] and ASHATTO T277 [2] specify the rating of chloride permeability of concrete based on the charge passed through the specimen during 6 h of testing period, as listed in Table 3. A charge value of less than 700 to 1000 C is typically specified, which is characterized as very low chloride permeability based on the rating in Table 3. However, some low water-to-cement ratio (0.3 to 0.4) conventional concretes cannot achieve the 700 to 1000 C. Yet, these same concretes exhibit negligible chloride penetrability when tested by the 90-day ponding test [11].

The other fact is that rating criteria are so different from place to place. The AASHTO Task Force on Strategic Highway Research Program (SHRP) implementation, in

Table 3
Rating of chloride permeability of concrete [1,2]

Chloride permeability	Charge (C)	Type of concrete	Total integral chloride to 41 mm depth after 90-day ponding test
High	>4000	High water-to-cement ratio (>0.6) conventional Portland cement concrete	>1.3
Moderate	2000–4000	Moderate water-to-cement ratio (0.4–0.5) conventional Portland cement concrete	0.8–1.3
Low	1000–2000	Low water-to-cement ratio (<0.4) conventional Portland cement concrete	0.55–0.8
Very low	100–1000	Latex-modified concrete, internally sealed concrete	0.35–0.55
Negligible	<100	Polymer-impregnated concrete, polymer concrete	<0.35

conjunction with the Federal Highway Administration (FHWA) and the Transportation Research Board, established a high-performance concrete (HPC) Lead State Team in 1996 to coordinate the use of HPC in bridges. Four members of the HPC Lead State Team—Nebraska, New Hampshire, Texas and Virginia—have specified different coulomb values from the RCPT results for high-performance bridge decks [51–54]: 1500 C after 180 days of curing in Virginia [51]; 1000 C after 56 days of curing in New Hampshire [51]; 2000 C after 28 days of curing in Texas [53] and 1800 C after 56 days of curing in Nebraska [54]. In one work in Texas [55], it is found that the 30% replacement of Portland cement by fly ash reduces the coulombs from 3230 to 1430 after 56 days of curing although the two batches of concrete have the same mixing proportion. Based on the coulomb specification, the concrete containing fly ash belongs to high performance, but the control one does not.

It is well known that the use of supplementary cementing materials, such as blast furnace slag, fly ash and silica fume, improve pore structure and reduce permeability of hardened concrete. However, results in Figs. 1–3 indicate that they can also have a significant effect on pore solution chemistry of hardened concrete. The transport of ions in concrete depends on the pore structure of the concrete, while the electrical conductivity of concrete or RCPT results depend on both the pore structure characteristics and the electrical conductivity of pore solution, which is determined by the composition of the pore solution. Thus, it is not correct to use electrical conductivity of concrete or RCPT results to rank the rapid chloride permeability of concrete containing supplementary cementing materials.

Materials such as silica fume, metakaoline and ground blast furnace slag are comparatively quite reactive and may significantly improve the pore structure and reduce permeability of concrete. However, fly ash and ground volcanic ash are much less reactive. The percentage of fly ash reacted is only between 10% and 20% and volcanic ash is between 15% and 30% at 90 days [55]. The reduction of coulombs of fly ash or natural pozzolan concrete before 90 days mainly result from the reduction of alkalinity of pore solution, rather than the reduction of permeability of concrete. In Virginia, it indicates high-performance concrete and encourages use of pozzolan to obtain lower coulombs [51]. The electrical conductivity or RCPT value of a concrete can be reduced by lowering the alkalinity of concrete pore solution, but concrete with a low electrical conductivity does not really mean that it has a low permeability.

4. Electrical conductivity and ion transport

The diffusivity of ions through a water saturated porous medium can be correlated with electrical conductivity as follows [56]:

$$\frac{D}{D_0} = \frac{\sigma}{\sigma_0} \tag{4}$$

where D = effective diffusivity of an ion in a porous medium, D_0 = diffusivity of the ion in a solution, σ = electrical conductivity of the solution saturated medium, and σ_0 = conductivity of the solution.

D_0 can be regarded as a constant for a given ion. The electrical conductivity of saturated concrete, σ, relies on the pore structure characteristics and the electrical conductivity of the pore solution in a hardened concrete, while σ_0 depends on water-to-cement ratio, hydration temperature, age, raw materials, etc. and cannot be determined easily. Thus, it is incorrect to use measured electrical conductivity to rate the ion penetration resistance of concrete made with different proportions or different materials.

5. Alternative test method

Many test methods have been proposed to assess the chloride permeability of hardened cement and concrete. They can be classified into four catalogues as summarized in Table 4. Streicher and Alexander [7] have reviewed most of those test methods and felt that the rapid migration test (RMT) method developed by Tang and Neilson [57] is a reliable and fast test method. The RMT has been standardized by Nordtest as NT Build 492. The test can be done with a similar apparatus as the RCPT. A chloride-bearing solution is placed on one side of the concrete sample and a chloride-free solution on the other side. A voltage, whose magnitude is applied based on the permeability of concrete sample, is applied to accelerate the migration of chloride through the concrete sample. At the end, the specimen was split and sprayed with $AgNO_3$ solution to determine the penetration depth of chloride. An evaluation test program at the University of Toronto [58] has found that the results from the RMT are not affected by the conductive ions in the

Table 4
Summary of the techniques for the measurement of Cl^- penetration in concrete

Test method	Sample thickness	Measurement	Test duration	Precision	Evaluation
Ponding test	Any	Chloride profile	Long	Approximate	Penetration depth, diffusion coefficient
Diffusion cell	Thin	Diffused Cl	Long	Accurate	Diffusion coefficient
Penetration depth	Any	Penetration front	Short	Approximate	Penetration depth, diffusion coefficient
Conductivity	50 mm, any	Current vs. time	Very short	Approximate	Passed charges conductivity

concrete pore solution and show lower variation than the RCPT results from the same batch of concrete despite the greater familiarity of the laboratories with the RCPT. Thus, the RMT should be standardized in North America to replace RCPT as soon as possible to provide valid evaluation of concrete materials.

6. Conclusions

The permeability of concrete depends on the pore structure of concrete, while electrical conductivity or resistivity of concrete is determined by both pore structure and the chemistry of pore solution. Factors that have little to do with the transport of chloride can have great effects on electrical conductivity of concrete. Thus, the electrical conductivity or resistivity of concretes cannot be used as an indication of their permeability. However, it can be used as a quality control indicator when the concretes have the same components and mixing proportions.

Supplementary cementing materials such as silica fume, fly ash and ground blast furnace slag may have a significant effect on the chemistry or electrical conductivity of pore solution, depending on the alkali content of the supplementary cementing material, replacement level and age, which has little to do with the chloride permeability.

The electrical conductivity of concrete decreases with an increase of volume of aggregate in concrete due to the dilution effect of conductive ions in pore solution and the adsorption of alkalis on the surface of aggregates. Some conductive ions can be extracted from aggregate into pore solution and increase the electrical conductivity of concrete.

The effective diffusivity of an ion in a hardened cement and concrete can be related with the electrical conductivity of concrete through some other parameters. However, these parameters are too difficult to be determined that it is practically not feasible to use the electrical conductivity of concrete as a direct indication of diffusivity of the ion.

The rapid chloride migration test (RMT) method has proven to be a rapid and effective test method for different types of concrete or concrete containing conductive materials, and should be used to replace the RCPT method.

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