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## The permeability of cement systems to chloride ingress and related test methods

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# The Permeability of Cement Systems to Chloride Ingress and Related Test Methods

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**ABSTRACT:** The rapid chloride permeability test (AASHTO T277/ASTM C 1202) and other chloride permeability testing methods are critically reviewed. The basic concepts of concrete permeability and conductivity are also discussed. An attempt at clarification and resolution of some issues is made. A faster and simpler alternative testing method to the AASHTO T277/ASTM C 1202 based on the a-c impedance techniques is proposed. It provides at least an equivalent indication of the concrete permeability with respect to AASHTO T277/ASTM C 1202 and is without several shortcomings characteristic of the current methods.

**KEYWORDS:** concrete, permeability, conductivity, resistivity, a-c impedance, rapid chloride permeability test, testing methods

The permeability in concrete is a material characteristic that has a significant influence on concrete durability, specifically freeze-thaw resistance, resistance to chemical attack, and alkali-aggregate reactions. It is considered an important indicator of concrete quality. The chloride permeability is of special interest as chlorides enhance steel reinforcement corrosion and are a major cause of deterioration in concrete structures. Various chloride permeability testing methods are critically reviewed. Concrete permeability and ion conductivity are discussed from the practical and fundamental viewpoints. A new, simple and rapid test method using a-c impedance methods to determine permeability is proposed.

## Factors Affecting Concrete Permeability and Conductivity

Concrete is porous and hence permeable to fluids. A great majority of the concrete durability problems involve solutions or aqueous media. The concrete permeability is controlled mainly by its microstructure (porosity, pore-size distribution, and tortuosity), whereas the electrical conductivity of ordinary concrete depends also on the ionic concentration of the pore solution.

Dry ordinary concrete has low conductivity; its conductivity increases sharply with increasing moisture content (Saleem 1996). Physically, electrical conduction of concrete can be considered to be ionic, i.e., a result of the motion or migration of *all* ions in its liquid phase. The saturated concrete can be considered as two phases with respect to the electrical conduction: solid phases (nearly non-conductive), such as unhydrated clinker grains, cer-

tain hydration products and aggregates, and the liquid phase (highly conductive) pore solution. The solid-liquid interfaces may have an impact on the electrical behavior of concrete in the electrical field, especially when the frequency of the electrical field changes dramatically.

The conductivity of the concrete liquid phase is governed by the total amount of the pore solution (a function of porosity), the transport path or distribution (pore connectivity and pore-size distribution), solution composition (ion types and their concentrations), and temperature (a major influence on the ion mobility and solubility). Any change of these parameters will affect the concrete conductivity.

The pore structure, pore solution composition, and ionic concentration in concrete change with maturity at earlier ages and very little at later ages. This means that the comparison of concrete permeability should be made with similar maturity, especially at earlier ages.

Chemical admixtures can alter the concrete pore solution. However, the pore solution behaves similarly to a buffer solution. Therefore, one can expect that certain types of chemical admixtures may have a larger impact on the pore solution conductivity than others. For example, the addition of calcium nitrate in concrete results in a higher conductivity, while the permeability remains nearly the same (ASTM 1995). The use of superplasticizers, in general, will significantly reduce the water demand in concrete and thus decrease the quantity of the pore solution.

Mineral additives, such as silica fume and fly ash, change both the microstructure and pore solution composition of the concrete. It is well known that the addition of silica fume and fly ash results in a finer pore structure in both the cement paste matrix and at the paste-aggregate interface in concrete (Mehta and GjØrv 1982; Malhotra et al. 1992; Farry et al. 1989). The addition of such additives also significantly reduces the pH value and the total ionic concentration of the pore solution in the long term (Page and Vennesland 1983; Diamond 1983; Wiens et al. 1995). The pH level of the pore solution in the Portland cement paste is about 13.8 ~ 13.9. For the pastes containing 30% silica fume replacing an equal mass of Portland cement, the pH level is about 12.4 or lower. Table 1 lists the selected ions, their concentrations, and changes with age and silica fume content in the pore solutions.

Different ions possess different mobility or conductivity. The conductivity of common ions in the pore solution is tabulated in Table 2 (Adamson 1979). Among the typical ions in the pore solution, the OH<sup>-</sup> ion is the most conductive, whereas the Cl<sup>-</sup> ion has only one third to two fifths the conductivity of the OH<sup>-</sup> ion. Therefore, the OH<sup>-</sup> ions contribute more than the other ions to the charge passed (total coulomb number) in the rapid chloride permeability test. Torii and Kawamura (1994) found that the charge passed in

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TABLE 1—Analysis of pore solutions from chloride-free pastes (Page and Vennesland 1983).

Pastes (W/C = 0.5)	Age, days	Ionic Concentration, mmole/L					Total Ion Concentrations, mg equivalents/L	
		Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	OH <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Cations	Anions
pure cement	7	263	613	1	788	23	876	834
	28	271	629	1	834	31	900	896
	84	323	639	2	743	27	966	797
10% silica fume	7	161	388	1	486	20	551	526
	28	101	209	0	241	40	311	321
	84	107	192	2	228	27	303	282
20% silica fume	7	109	231	1	290	23	342	336
	28	59	109	1	91	33	170	157
	84	51	69	2	78	25	124	128
30% silica fume	7	75	143	1	152	33	220	218
	28	35	53	2	26	35	92	96
	84	30	30	7	10	32	74	74

TABLE 2—Equivalent conductivity of aqueous ions at 25°C (Adamson 1979).

Ion	Na <sup>+</sup>	K <sup>+</sup>	Ca <sup>2+</sup>	OH <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Cl <sup>-</sup>
Equiv. conductivity, m <sup>2</sup> equiv. <sup>-1</sup> ohm <sup>-1</sup>	0.00501	0.00735	0.00595	0.0198	0.00798	0.00763

coulombs decreases remarkably with reduction in OH<sup>-</sup> ion concentration.

The rapid chloride permeability test actually measures the electrical conduction of all the ions, and not just the chloride ion. Pfeifer's observation (1993) that silica fume may only marginally reduce the amount of chloride intrusion during the 90-day ponding test (even though very low coulomb values are obtained for such concrete) can be explained. This is attributable mainly to the fact that silica fume significantly reduces the quantity or total number of ions (total ion concentrations in Table 1), especially the OH<sup>-</sup> ion, in the pore solution; these ions carry the charge under the electrical field. Therefore, it is necessary to establish a separate criterion for concrete-containing mineral additives when using electrical methods to assess permeability.

#### An Assessment of Existing Chloride Permeability Tests

A popular rapid chloride permeability testing method was developed by Whiting (1981). Later, this method was standardized as the AASHTO Standard T277 in 1983 (AASHTO 1983) and as the ASTM Standard C 1202 in 1991 (ASTM 1995). The test involves measuring the amount of electrical current that passes through a thick disk of material when one end of the disk is exposed to a sodium chloride solution and the other end to a sodium hydroxide solution. A potential difference of 60-V dc is normally maintained across the specimen for 6 h. The total charge passed, in coulombs, is measured and related to chloride permeability.

The rapid chloride permeability test (referring to AASHTO T277/ASTM C 1202) has been widely used. Its use has been the subject of considerable debate. The debate focuses on two problems: (1) the theoretical tenets and intrinsic effects, including the temperature rise during the test; and (2) interpretation of results for concrete systems containing various chemical and mineral admixtures. The debate not only concerns the theoretical fundamentals of ionic diffusion, conduction, and migration, but also involves the basic understanding of concrete materials.

#### Theoretical Considerations

Permeability is the capacity of a porous material for transmitting a fluid under the influence of a given pressure. Diffusion is the process resulting from random motion or spontaneous movement of molecules by which there is a net flow of matter from a region of high concentration to a region of low concentration. By definition, permeability and diffusion are different. However, they are "related" in some way under certain conditions, since they both represent properties with respect to the flux. Concrete in the dry state possesses permeability, but has no bulk diffusion (through solution) at all. Only in the completely saturated concrete, when all pores are filled with water (solution), the ionic diffusion through bulk concrete (through solution in pore spaces actually) is "related" to permeability in terms of a numerical value, but they are still different phenomena. In practice, both permeability and diffusion in concrete are measured in the saturated condition. As a result, it appears that there exists some kind of numerical relationship between them. This might be the reason that permeability and diffusion are often used interchangeably in the literature in the field of concrete science, which may cause some confusion. Such a usage is technically wrong, but actually practiced.

The rapid chloride permeability test is actually a measure of the migration or conduction of the total salt ions in the pore solution, and not exclusively the chloride diffusion. This is due to the high voltage potential (typically 60-V dc) applied. The flux may not be in the steady-state condition. Thus, the results may not represent the "real" chloride ion diffusion in concrete. Furthermore, the temperature rise during the test increases the ion conduction rate and may change the microstructure. Hence, it could lead to an exaggerated result. The temperature rise effect may be less significant for low-permeability concrete than for a highly permeable one. In the former case, the low initial current leads to a limited temperature rise. In the latter case, however, the temperature due to the high electrical current is sufficiently high that the test could be terminated within a few hours.

Fick's first law can be applied to the diffusion test to calculate the chloride diffusion coefficient if the diffusion process is in the steady state. In order to approach the steady-state diffusion and/or limit the temperature rise, a very thin specimen, e.g., 0.5 cm as used by Andrade (1993), or a low voltage potential, e.g., 10 V as suggested by Dhir et al. (1990) or 12 V as described by Detwiler et al. (1991, 1993), should be used. However, this may cause some practical problems: (1) the concrete specimen may be too thin to be representative of concrete containing large aggregates; (2) the process to reach the steady-state diffusion may be time-consuming, e.g., several days or longer in comparison with 6 h in the rapid chloride permeability test.

Other test methods use fundamental theories to overcome the above shortcomings. In these methods, the diffusion coefficients are obtained by solving the non-steady-state diffusion equations (e.g., Fick's second law using Tang and Nilsson's method (1992) or the Nernst-Planck or Nernst-Einstein equations (in the method proposed by Andrade et al. (1994). These methods appear to be more fundamentally sound, but not as simple as the rapid chloride permeability test. Streicher and Alexander (1995) suggested a rapid chloride conduction test based on sound theoretical arguments. The testing itself (or measuring process) is fast. The sample conditioning procedure, however, seems to be problematic. In their method, the concrete samples are dried in an oven at 50°C for 7 days, vacuum saturated in 5 M NaCl solution for 5 h, and then left to soak in the solution for an additional 18 h. This 8 days conditioning procedure is lengthy, compared to only about 1 day of conditioning in the rapid chloride permeability test. In addition, the 7-day drying procedure at 50°C would introduce drying cracks into the concrete samples and possibly alter the pore structure. Thus, it might interfere with the actual chloride diffusion or migration profile.

It appears that the various methods to determine the diffusion coefficient are not very practical, even if they are fundamentally sound. These methods are generally relatively complex and time-consuming. They are also sensitive to small and local defects, such as cracks in the concrete samples. Most methods for determining diffusion coefficients involve the measurement of the chloride concentration profile along the longitudinal axis of the concrete disk. Small and local defects may alter the transport path of the chloride ion locally and hence change the concentration profile. As a result, the "apparent" diffusion coefficient calculated from that profile may markedly deviate from its "intrinsic" value. In addition, these defects are much easier to control under laboratory conditions than in the field. This adds another variable to the application of the (diffusion coefficient) methods in practice.

#### Concrete Systems Containing Chemical and Mineral Admixtures

AASHTO T277 and ASTM C 1202 are essentially equivalent. Both methods employ the same criteria, as shown in Table 3. The latter, however, recognizes the necessity to correlate the results of

TABLE 3—Chloride ion penetrability based on charge passed (Whiting 1981).

Charge Passed, coulombs	Chloride Ion Penetrability
>4,000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very low
<100	Negligible

electrical charge with those of the long-term chloride ponding test (AASHTO T259 (AASHTO 1993). The testing used to develop this standard method and its criteria, however, did not include any concrete containing mineral admixtures or superplasticizer (HRWR) (Scanlon and Sherman 1996). These are commonly used in modern concrete making, that is, the criteria do not reflect the effects of those admixtures.

The rapid chloride permeability test actually measures the electrical properties (current passed or conductivity) of the concrete. Therefore, any factor that influences the electrical properties of concrete will affect the result, i.e., the total coulomb number. It is well known that the addition of silica fume into concrete will reduce the permeability. However, as Pfeifer (1993) argued, the very low coulomb values for silica fume concrete could be misleading, since the ponding test results show only marginal reduction in chloride penetration. This is in spite of the very low coulomb values obtained for such concrete. An attempt to explain this apparent anomaly is made in this work.

The relationship between the rapid chloride permeability test results (coulombs) and those of the penetration test (e.g., the long-term chloride ponding test) is not clear for concrete-containing mineral and chemical admixtures. Scanlon and Sherman (1996) found substantial differences between the results of the AASHTO T277 and the AASHTO T259 (long-term ponding test) for concrete containing silica fume, fly ash, and high-range water reducer (HRWR). They concluded that the general correlation between the coulomb value and chloride penetration appears invalid for such concrete. Nail et al.'s data (1994) also showed that there is no clear correlation between the coulomb value and water permeability for concrete containing large amounts of fly ash. However, Ozyildirim (1994) demonstrated a fairly good agreement between the rapid chloride (coulomb) test and the long-term ponding test for silica fume concrete. Berke (1988) arrived at a similar conclusion, although the agreement was qualitative. Furthermore, Berke et al. (1988) indicated a fairly good correlation between the rapid chloride (coulombs) test results and the effective diffusion coefficients. Myers et al. (1997) also obtained a good linear correlation between total coulombs (the rapid chloride test) and amount of chloride penetration (the long-term ponding test). They suggested that the rapid chloride test should not be used as a sole indicator of permeability for specific concrete mixes without correlating it with the long-term ponding test. A similar caution is also issued in ASTM C 1202.

In summary, the rapid chloride permeability test (AASHTO T277/ASTM C 1202) has been used widely at the expense of the ponding test (AASHTO T259) (AASHTO 1996). The key point here is that the rapid chloride permeability test results are fast, simple, and hence practical. "Whatever property it is measuring probably is coincident with permeability," noted Hooton (1989). Misuse of this test and misinterpretation of the results are, however, common due to misunderstanding of fundamentals and lack of quality information on influence of mineral and chemical admixtures on the electrical properties of concrete. Therefore, it is important to clarify the fundamental principles underlying the concrete permeability and its electrical properties. It is also desirable to develop a faster and simpler, but less problematic method for assessing concrete permeability and quality.

#### Application of the a-c Impedance Technique to Cement Systems

The a-c impedance spectroscopy technique has been applied to cement and concrete systems to characterize pore structure. Gu et

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al. (1995) provided a comprehensive summary of its applications in the cement and concrete science. The key elements of the technique, which are used to develop the basis for a new permeability test (to be discussed later), are highlighted briefly here.

A very small amplitude sinusoidal voltage or current signal is applied to the test system, and the resulting response potential or current signal is recorded. A schematic of an a-c impedance spectrum (for a cement system) is illustrated in Fig. 1 (Gu 1995).

The high-frequency arc (HFA) is attributed to the bulk paste or concrete impedance behavior, and the second arc is due to the capacitance of the paste or concrete-electrode interface. The HFA diameter,  $D_{HFA}$ , is determined from the equivalent circuit modeling, as shown in Fig. 1b. The low-frequency intercept on the real impedance axis,  $R_1 + R_2$ , an important parameter referring to the "true" d-c bulk resistance, depends on the materials and their proportions (cement paste, aggregates, admixtures, pore solution, etc.), microstructure (porosity, pore-size distribution, solid-liquid interfaces), and temperature.

In this sense, the value obtained by the rapid chloride test is only at best a d-c resistance of sorts and should be compared against this value.

The low-frequency intercept impedance can be regarded as a microstructural descriptor of the particular system tested. The frequency,  $\omega$ , at which the low-frequency intercept is obtained, is not fixed. It varies for different systems, such as the neat cement paste and silica fume concrete, and at different ages. For example, the frequency of the high intercept for the neat cement paste is in the range of 2000 ~ 4000 Hz, while for the silica fume paste, this frequency ranges from 500 to 10 000 Hz, depending on the paste age and specimen size. The impedance at a given frequency is not necessarily equal to the low-frequency intercept impedance. Most reported impedance data were measured at a fixed frequency, e.g., 1 kHz, which could be different from the low-frequency intercept impedance. It is the main reason that the a-c impedance spectroscopy is considered superior to the impedance measurement de-

vice at fixed frequencies and recommended in the proposed testing method. In other words, the advantage of using the a-c impedance spectroscopy is to obtain a spectrum of impedance with a broad range of frequencies so that the low-frequency intercept impedance can be accurately determined.

## The Total Charge-Initial Current Relation

### Individual Concrete Specimens

In the rapid chloride permeability test, the total charge passed in coulombs,  $Q$ , is a function of the electrical current,  $I$ , and the time,  $t$ , as expressed by

$$dQ = I dt \quad (1)$$

or

$$Q = \int I dt \quad (1')$$

The terms used in the expressions that follow are:

$I_0$  = initial current, i.e., the current at  $t = 0$ ,

$V$  = voltage applied between the concrete disk ends,

$V_0$  = initial voltage, i.e., the voltage at  $t = 0$ ,

$R$  = resistivity of the saturated concrete disk,

$R_0$  = initial resistivity, i.e., the resistivity at  $t = 0$ ,

$\sigma$  = conductivity of the saturated concrete disk,

$\sigma_0$  = initial conductivity, i.e., the conductivity at  $t = 0$ ,

$\sigma = 1/R$ .

In principle, Ohm's law is considered both as an ideal law and as a limiting law for small voltage and current. It is well obeyed by all substances provided the energy dissipated does not cause appreciable local heating. The electrolyte solutions start to deviate from Ohm's law at high voltages. During the rapid chloride permeability test, the current,  $I$ , changes with time, while the voltage,  $V$ , remains approximately constant for most concretes if the capacity of the power supply is large enough. That is, one can assume that  $V = V_0$ . Therefore, the following expression (i.e., Ohm's law) would be approximately valid for most cement and concrete systems at the very beginning of the test or provided the initial current is not very high.

$$I = V/R = V_0/R \quad (2)$$

or

$$I = V\sigma = V_0\sigma \quad (2')$$

In fact, as discussed in the latter section, the experiments have verified Eqs 4, 5, and 5'. As a result, the validity of Eqs 2 and 2' is indirectly confirmed, at least for the very beginning of the test.

For extremely porous concretes, the initial current is very high, and the voltage drop may be significant. Equations 2 and 2' begin to fail. These cases will be discussed later in this section.

During the test, the temperature of the specimen rises, and the conductivity increases with temperature. The temperature dependency of conductivity can be empirically written as (Bockris and Reddy 1970; Sawaby et al. 1988; Whittington et al. 1981):

$$\sigma(T) = A \exp(-\Delta E/k_b T) \quad (3)$$

where  $A$  and  $\Delta E$  are empirical constants. The latter can be considered as the activation energy of the reaction process. The term  $k_b$  is Boltzmann's constant and  $T$  is the absolute temperature. In order to confirm this relationship for neat cement and silica fume pastes, a

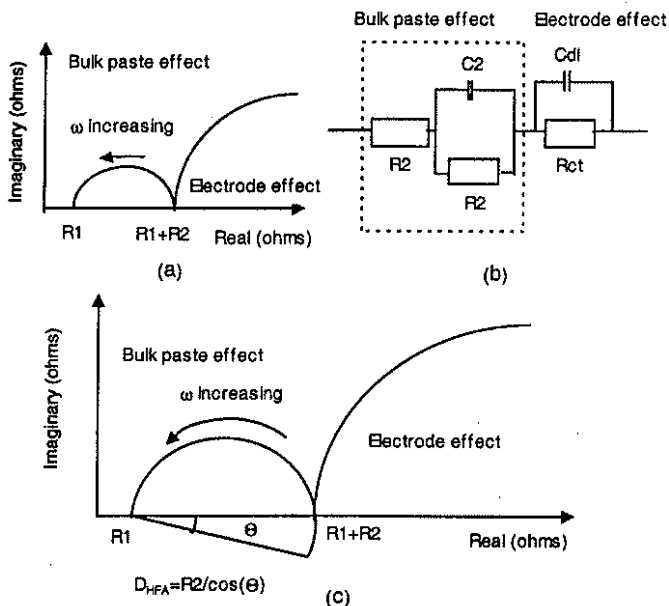


FIG. 1—(a) Schematic plot of a high-frequency arc in the impedance complex plane obtained for cement paste or concrete systems; (b) the corresponding electrical equivalent circuit; and (c) more general spectrum featuring an inclined semicircle whose center is depressed below the real axis by an angle  $\theta$  (Gu et al. 1995).

series of tests were conducted. In the tests, the voltage remained nearly the same. According to Eq 2', if the  $\log I - 1/T$  relation is linear, the  $\log \sigma - 1/T$  relation should also be linear. Figure 2 demonstrates that the experimental  $\log I$  versus  $1/T$  plots are essentially linear and hence confirms that Eq 3 is actually valid for the cement paste systems. Based on the data in Fig. 2 (Liu et al. 1999), the activation energy of electrical conduction for the neat paste and for the silica fume paste is  $1.602 \times 10^{-20}$  J and  $0.275 \times 10^{-20}$  J, or 0.257 and 0.0412 eV, respectively. An activation energy of electrical conduction for the zinc polycarboxylate cement has previously been estimated to be 0.22 eV (Sawaby et al. 1988).

Equation 3 is similar in form to the basic temperature-reaction rate relationship, i.e., the Arrhenius equation. This appears to imply that the electrical conduction through the concrete pore solution is a thermally activated, reaction rate-controlled process.

#### Various Cement and Concrete Systems

Other experimental data (Feldman et al. 1994; Fukute et al. 1996), including the authors (Liu et al. 1999), demonstrated that a linear relationship between the total charge passed (coulombs) and the initial current exists for various cement paste and concrete systems with and without mineral additives. Mathematically, this relationship can be written as

$$Q = A + BI_o \quad (4)$$

where  $A$  and  $B$  are empirical constants that depend on the specific materials, their proportions, and microstructure, etc.

For the extremely porous concretes, the high current leads to a dramatic temperature rise and/or causes a significant voltage drop due to the limit of the power supply capacity. This linear relationship may no longer be valid. For such concretes, however, the high permeability can be immediately noticed without a necessity to obtain the exact numerical values.

In principle, the initial current should be directly related to the conductivity or inversely related to the resistivity of the saturated concrete (see the discussion in the previous section). The linear relation of initial current versus initial conductivity or versus the re-

ciprocal of initial resistivity has been confirmed by numerous experiments (Liu et al. 1999; Fukute et al. 1996; Zhao et al. 1998) with high linear correlation coefficients. Hence, Eq 4 can be expressed as

$$Q = a + b\sigma_o \quad (5)$$

or

$$Q = a + b/R_o \quad (5')$$

The linear relation for concrete containing mineral additives may differ in constants  $a$  and  $b$  from that for concrete without such additives, according to the previous discussion on the pore solution chemistry.

Feldman's results (Feldman et al. 1993) indicated that the relation between electrical conductivity and chloride diffusivity appears to be linear for blended cement mortars. Therefore, the importance of these linear relations, particularly Eqs 5 and 5', is obvious. They provide a promising opportunity to develop a much faster and simpler concrete permeability test using a-c impedance spectroscopy. The impedance measurement takes only a few minutes or less! A concept for quality assessment similar to the rapid permeability test was suggested by Zhao et al. (Zhao et al. 1998).

#### A Proposed Concrete Permeability Test

The main features of the proposed testing method are as follows:

- Measurement of the impedance (conductivity) of the saturated concrete, which is related to permeability.
- Effects of chemical and mineral admixtures taken into account.
- Much faster and simpler procedures than the rapid chloride permeability test (AASHTO T277/ASTM C 1202)—the result is obtained within minutes.
- An equivalent indication of relative permeability to that obtained by the rapid chloride permeability test.
- No heat and therefore no microstructural changes generated during the test.

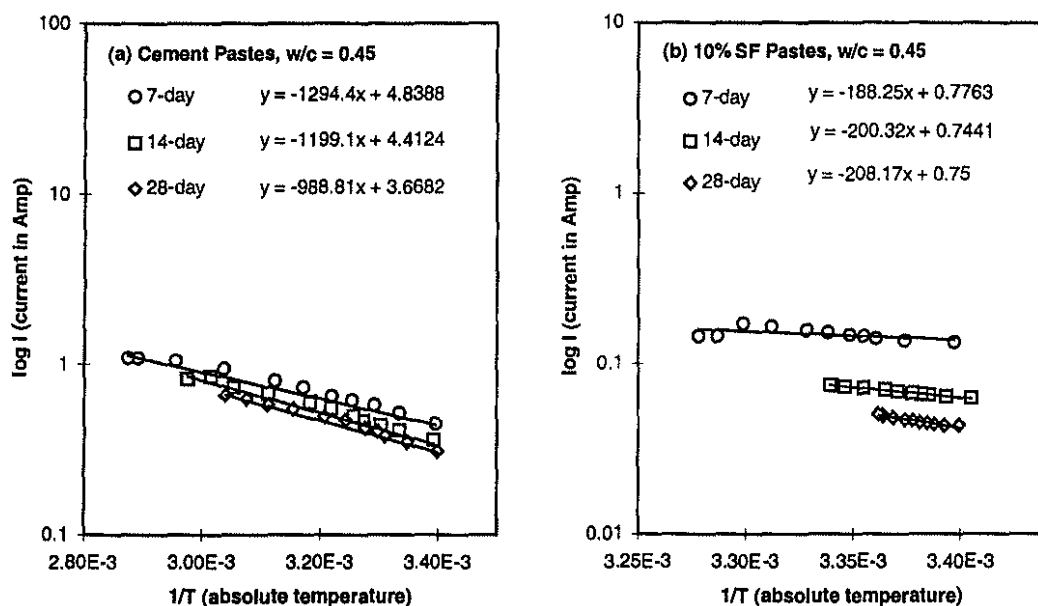


FIG. 2—The relationship between  $\log I$  and  $1/T$ .

### Sample Preparation

The disk-type specimen ( $\phi 102 \times 51$  mm), as described in the AASHTO T277/ASTM C 1202 method, should be appropriate. The size and shape of the specimen are not critical (as long as both ends are flat, parallel, and equally sized) since the result is reported in normalized units.

The specimen saturation procedure would be the same as in the AASHTO T277/ASTM C 1202 method to ensure that the concrete specimen is completely saturated.

The surface of both ends of the specimen disk should be as flat as possible to ensure good contact with the plate electrodes.

### Apparatus and Equipment

A plate-shaped electrode would be used. The electrode would be made from flat metal sheet, for example, a stainless steel plate. Its size would be slightly larger than the disk diameter.

An a-c impedance spectroscope or analyzer would be employed to obtain the impedance spectrum with a proper range of frequency.

### Measurement

One electrode would be placed on each end of the specimen disk. A good contact between the electrode plate and the surface of the specimen disk ends should always be maintained. For example, applied pressure on the electrode plates, and a wet, thin sheet of soft fabric, such as a paper towel placed between the electrode plate and the specimen if necessary, would improve measurement accuracy.

### Reporting of Results

The high intercept impedance on the real axis of the spectrum is recorded and then normalized as resistivity in  $\Omega\cdot m$  taking into account the specimen size (diameter and length). This value of resistivity is size-independent.

The specimen maturity (age and curing temperature), components (mix design), and other important information should also be recorded and reported.

### Assessment Criteria

Two sets of assessment criteria are necessary—one for plain concrete and the other for concrete containing supplementary cementing materials. The first set would be designed for concrete without mineral admixtures and would be similar in form to the criteria set out in Table 3 (the AASHTO T277/ASTM C 1202 method). The difference lies in the use of resistivity levels instead of the coulomb values. The second set is suited to the concrete containing the mineral additives and would recognize the significant impact of such additives on the concrete conductivity, the chemistry of the pore solution, and the microstructure.

The concept of two sets of assessment criteria is verified by Myers et al.'s work (Myers 1997). In their results (Fig. 8 of Myers 1997), it is obvious that two parallel trend lines exist in the correlation between coulombs and chloride ion content (penetration). One straight line exists for concrete without fly ash, and the other line for concrete containing fly ash, as illustrated in Fig. 3. For the same level of chloride ion content, the concrete without fly ash shows higher coulombs values (approximately 300 to 350 C higher) than the concrete containing fly ash.

According to our studies (Fukute et al. 1996), the naphthalene sulfonate-type of superplasticizer slightly increases conductivity for pastes containing silica fume, but not significantly. It is inferred

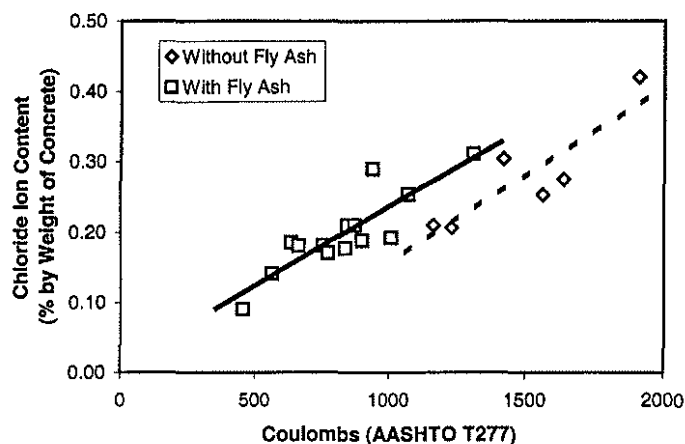


FIG. 3—Correlation between coulombs and chloride ion content of concrete with and without fly ash (redrawn from Fig. 8 in Myers et al. 1997).

that separate criteria for concrete containing these superplasticizers would not be necessary.

Two tables of the suggested assessment criteria could be constructed (for concrete with and without mineral additives). The actual values of resistivity (impedance) form the basis for a concrete permeability noting of high, moderate, low, and negligible.

It is not difficult to correlate the total coulombs to the resistivity values since both reflect basically the same electrical property of concrete. An alternative criteria table (Table 3) (AASHTO T277/ASTM C 1202) has already been proposed (Zhao 1998). However, it appears to be too simplified. As discussed previously, the electrical property (resistivity or total coulombs) is an indication of the "relative" permeability and is affected strongly by the presence of the mineral additives, etc. The presence of the mineral additives results in very low readings of the total coulombs or high readings of resistivity through altering the pore solution chemistry (the total ionic concentration) even if the actual permeability may not be reduced significantly. Therefore, it is advised that these criteria be linked to the results of the long-term ponding test (AASHTO T259), rather than simply to the total coulombs (AASHTO T277/ASTM C 1202).

A list of factors that can produce misleading results is given in Section 5 of ASTM C 1202. This list should be updated and expanded regularly to accommodate the latest results.

### Applications of the Proposed Testing Method

The proposed method could be considered as:

- An alternative method to AASHTO T277/ASTM C 1202.

An index of relative permeability, similar to that by AASHTO T277/ASTM C 1202, can be obtained within minutes and without the heat generation during the test.

- A means of concrete quality control and assessment.

The proposed method can be easily employed in the field by the design of the proper shape of electrodes. The measurement is non-destructive.

### Concluding Remarks

The concrete permeability depends mainly on its microstructure (porosity, pore-size distribution, and tortuosity). The electrical

conductivity of concrete is governed by its microstructure and the chemistry of the pore solution, that is, ion types and their concentrations.

The addition of mineral additives, such as silica fume and fly ash, can significantly reduce the pH value and the total ionic concentration of the pore solution in the mature concrete. As a result, the addition of such additives lowers the total coulombs significantly in spite of only marginal reduction in permeability to ions such as chloride. Therefore, two assessment criteria are needed for any permeability testing method based on the measurement of concrete electrical properties: one for plain concrete and the other for concrete containing mineral additives.

The electrical conduction in concrete (through the pore solution) is a thermally activated, reaction rate-controlled process. The total coulombs and resistivity of concrete are basically equivalent, and the latter is much easier to measure. This provides an alternative simple and rapid method for the assessment of the "relative" permeability of concrete with respect to AASHTO T277/ASTM C 1202. The proposed method is based on the resistivity measurements using the a-c impedance techniques and is without several shortcomings characteristic of the current methods.

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