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A virtual rapid chloride permeability test

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Abstract

The rapid chloride permeability test (RCPT), as it is commonly called, has been in existence for over 20 years and was standardized by ASTM over 15 years ago. The test is used extensively in the concrete industry for assessing concrete quality and is now being included in concrete specification documents. Because the underlying physics of the test are fairly well understood, it is possible to create a virtual test method that mimics the real world physical test. This paper presents a prototype virtual test method that includes prediction of the conductivity of the cementitious binder pore solution and the total charge passed during an ASTM C1202 RCPT. Potential applications of the virtual test method are first discussed. Then, the technical background used and the numerous assumptions employed in creating the prototype virtual test are outlined in detail. In addition, the computer implementation of the virtual test, as a set of HTML/JavaScript web documents, is presented. Validation against existing data sets is presented, with a generally reasonable agreement noted between the experimental and the virtual test results.
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1. Introduction

Originally developed in the early 1980s [1] and standardized as ASTM C1202 in 1991 [2], the rapid chloride permeability test (as it is commonly called) is now being used extensively in specifications, quality control, and concrete durability research [3]. While the shortcomings of the test are numerous and have been critically assessed by several authors [4,5], the current widespread usage of the test and the fact that is has been standardized suggest that it will continue to be one of the evaluators of concrete performance of choice for the foreseeable future. Based on a measurement of the electrical conductance of a cylindrical concrete specimen, the underlying physics of the measurement are sufficiently understood that it is possible to develop a virtual test method that simulates laboratory performance. This paper describes a hypertext markup language (HTML)/JavaScript-based virtual test method that has been developed and is freely accessible via the Internet at http://ciks.cbt.nist.gov/VirtualRCPT.html. Following the presentation of the technical basis for the virtual test, both verification and validation [6] will be examined. Since many assumptions have been made to create this first generation virtual test method, a further goal of the paper is to document and substantiate these assumptions.

It is envisioned that the RCPT virtual test method presented in this paper could be employed in the following manners:

(1) In conjunction with ACI 211 [7], to estimate the electrical conduction of proportioned concrete mixtures. Actually, ACI 211 could be considered as a virtual test method for predicting the compressive strength of concrete. The mixture proportions (for obtaining a user-specified strength) returned by the 211 procedures in either manual or computerized form [8] could be input into the RCPT virtual test method to provide some indication of their projected performance in the C1202 test.

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(2) As an educational tool for the concrete community to provide insight into what factors critically influence the results of a RCPT (pore solution conductivity, degree of hydration, temperature, etc.) and explore the influences of mixture proportions. (If a user increases their cement content by 50 kg/m^3, what will be the effect on the total charge passed in the C1202 test? What if a small addition of silica fume is employed instead?)
(3) As a tool to examine proposed modifications to and variations of the C1202 test method. (How do the results change if the total charge passed is recorded after only 15 min or 30 min instead of 6 h? What if this testing time is further reduced to 1 min?)

2. Virtual test basis

The ASTM C1202 standard test method for electrical indication of concrete's ability to resist chloride ion penetration [2] monitors the amount of electrical current that is passed through a cylindrical concrete specimen when a 60 V dc potential difference is applied across the specimen for a period of 6 h. The measured current vs. time data is integrated (generally numerically or via automatic data processing equipment) to obtain the total charge passed in coulombs. If the diameter of the test specimen is different from the specified 3.75 in. (95.25 mm), the calculated result is adjusted to that which would be expected for a 3.75 in. (95.25 mm) diameter specimen by multiplication by a simple areal ratio. Five levels are identified to classify the charge passed as corresponding to chloride ion penetrabilities of "high, moderate, low, very low, or negligible".

Under the testing configuration specified in C1202, the current passed through the concrete cylinder is determined by the simple application of Ohm's law [9]:

$$V = iR, \quad i = VG, \tag{1}$$

where V is the applied voltage (60 V), i is the current in Amperes, and R is the resistance of the specimen in Ohms. The conductance of the specimen, G, is defined as $1/R$ and has units of siemens (S).

The conductivity of the concrete specimen, σ_{specimen} (in units of S/m), can be computed as [5]

$$\sigma_{\text{specimen}} = \frac{GL}{A}, \tag{2}$$

where L is the specimen length in meters and A is the exposed area in square meters. For the ASTM C1202 test method, L and A are nominally 0.051 m and 0.007126 m^2, respectively. By far, the major components of electrical conduction through the concrete specimen are the pathways that are saturated with cement pore solution. The conductivity of the concrete specimen can thus also be represented by [10]

$$\sigma_{\text{specimen}} = \frac{\sigma_{\text{poresoln}}}{F}, \tag{3}$$

where the formation factor F is defined as the ratio of the pore solution electrical conductivity to the specimen conductivity. Eq. (3) highlights the fact that the results of a RCPT depend both on the microstructure of the concrete (F) and the conductivity of the pore solution. Thus, a concrete based on a low-alkali cement should exhibit a lower value when tested according to the RCPT protocol, even when it exhibits the same microstructure as one produced using a high-alkali cement. This is one of the commonly cited limitations in utilizing the RCPT, a measure of electrical conduction, to assess diffusive transport in cement-based materials [1,5]. From Eqs. (1)–(3), it is hopefully clear that if one were to know F and σ_{poresoln}, the current passed (and ultimately the total charge passed $= \int^{\tau} i(t)\mathrm{d}t$, where τ is the total testing time) through the concrete specimen during the rapid chloride permeability test (RCPT) could be predicted in a virtual test environment. The next two subsections will present the procedures that are currently employed for estimating these two quantities from concrete mixture proportions and material characteristics. Additionally, the effects of the temperature rise that commonly occurs during an ASTM C1202 test will be examined and preliminarily accounted for in the virtual test method.

2.1. Formation factor

The prediction of the concrete formation factor can be aided by the relationship between electrical conduction and ionic diffusion as described by the Nernst–Einstein equation [11]:

$$\frac{D_{\text{specimen}}}{D_{\text{poresoln}}} = \frac{\sigma_{\text{specimen}}}{\sigma_{\text{poresoln}}}, \tag{4}$$

where D_{specimen} is the diffusivity of (some) ionic species in the concrete specimen and D_{poresoln} is the corresponding diffusivity of that ionic species in bulk pore solution. Previously, based on experimental measurements and computer modeling, the following equation has been developed for estimating the diffusivity of chloride ions in concretes containing silica fume as a function of water-to-cement ratio by mass (w/c), condensed silica fume *addition* rate by mass fraction (CSF), degree of cement hydration (α), and volume fraction of aggregates (V_{agg}) [12,13]:

$$\begin{aligned}\log_{10}(D_{\text{specimen}}) = \Big(&-13.75 - 0.82\frac{w}{c} + 32.55\left(\frac{w}{c}\right)^2 \\ &+ 8.374\text{CSF} + 15.36(\text{CSF})^2 \\ &+ 23.15\left(\frac{w}{c}\right)\text{CSF} + 5.79\alpha - 21.1\left(\frac{w}{c}\right)\alpha \\ &- 43.15(\text{CSF})\alpha - 1.705V_{\text{agg}}\Big).\end{aligned} \tag{5}$$

In Eq. (5), *w*/*c* includes only the portland cement component of the binder and not the silica fume [13]. Taking the diffusivity of chloride ions in bulk water as

1.8×10^{-9} m^2/s at 20 °C [14], Eq. (5) can be rewritten in terms of the ratio of the two diffusivities as

$$\log_{10}\left(\frac{D_{\text{specimen}}}{D_{\text{poresoln}}}\right) = \left(-5 - 0.82\frac{w}{c} + 32.55\left(\frac{w}{c}\right)^2 + 8.374\text{CSF} + 15.36(\text{CSF})^2 + 23.15\left(\frac{w}{c}\right)\text{CSF} + 5.79\alpha - 21.1\left(\frac{w}{c}\right)\alpha - 43.15(\text{CSF})\alpha - 1.705V_{\text{agg}}\right). \tag{6}$$

It should be kept in mind that Eq. (5) was developed for *w*/*c* ranging from 0.3 to 0.5, silica fume additions from 0.0 to 0.1, aggregate volume fractions from 0.62 to 0.70, and degrees of hydration from 0.6 to 0.9. Extrapolation beyond this parameter space should be performed with caution. In the prototype virtual test method, Eq. (6) is used along with Eq. (4) to provide an estimate of the formation factor of the concrete specimen, the first parameter needed for estimating the total charge passed in the RCPT. For usage in the virtual test system, the V_{agg} of a concrete mixture proportion is adjusted to also include the air void content of the concrete, as from a diffusion or electrical conduction viewpoint, air voids in concrete should function equivalently to aggregates unless they become saturated; it has been demonstrated previously that the interfacial transition zone formed at the air void surfaces is similar to that formed at the surfaces of aggregates [15].

In applying Eq. (6) in the virtual test method, it is assumed that fly ash functions similarly to but less efficiently than silica fume; thus, CSF is computed as the sum of the silica fume addition rate (multiplied by its SiO_2 fractional content by mass) and the fly ash addition rate multiplied by both its SiO_2 fractional content and an efficiency factor of 0.5. Because the HTML pages comprising the virtual test method are directly downloadable to a user's computer, the user may easily change this efficiency value from 0.5 to a value of their choosing. For computing an effective *w*/*c* for use in Eq. (6), slag is assumed to be equivalent to cement (efficiency factor = 1.0) and the remainder of the fly ash not assigned as equivalent silica fume as described above is assumed to be equivalent to cement.

The (28 d) degree of hydration in Eq. (6) is estimated based on the effective *w*/*c* as

$$\alpha = 0.65 + 0.1\frac{(\frac{w}{c} - 0.39)}{(0.45 - 0.39)} \tag{7}$$

and further limited to be within the range of [0.55, 0.95]. This base degree of hydration is further modified based on the fineness of the cement. If the Blaine fineness of the cement is greater than 400 m^2/kg, the degree of hydration computed by Eq. (7) is further increased by 0.05; if the fineness is less than 350 m^2/kg, it is decreased by 0.025. As other equations exist for estimating this degree of hydration [16], within the virtual test method, the user has the option of overriding this estimated degree of hydration value with a value of their own choosing and recomputing (using a *Recompute* button) the total charge passed during the RCPT. For an ordinary portland cement blended with slag and/or fly ash, the degree of hydration should represent a mass-weighted average for the three components, keeping in mind that the reactivities of slags and fly ashes can potentially be much lower than that of a typical ordinary portland cement [17,18].

2.2. Pore solution conductivity

The major contributions to the conductivity of the pore solution in a cement-based material are generally those of three ions: potassium (K^+), sodium (Na^+) and hydroxide (OH^-). Snyder et al. [10] have developed a straightforward procedure for estimating pore solution conductivity from the concentrations of these three ions in the pore solution. Thus, the first step is to implement an algorithm for estimating these concentrations. Starting from the measured oxide compositions of the cementitious materials (cement, silica fume, fly ash, and slag) and the known mixture proportions, the following computations are utilized.

First, the oxide compositions are converted to moles of ions per gram of material using

$$N_{\text{Na}^+} = \frac{2m_{\text{f}}^{\text{Na}_2\text{O}}}{(2 * 22.9898 + 15.9994)}, \tag{8}$$

$$N_{\text{K}^+} = \frac{2m_{\text{f}}^{\text{K}_2\text{O}}}{(2 * 39.0983 + 15.9994)}, \tag{9}$$

where *N* indicates the moles of a specific ion per gram of binder, m_{f} the mass fraction of the specific oxide (mass of oxide per unit mass of binder), and 22.9898, 39.0983, and 15.9994 correspond to the molar masses of sodium, potassium, and oxygen, respectively. Eqs. (8) and (9) are applied individually to all of the reactive components of a blended cement mixture including cement, silica fume, fly ash, and slag.

To compute concentrations, the next step is to compute the volume of pore solution present in the concrete per unit mass of binder, v_{PS}. For a pure ordinary portland cement system under *saturated curing* conditions, a mass balance on the water (per unit mass of cement) gives

$$\text{Water\_left} = \text{starting\_water} - \text{hydration\_bound\_water} + \text{imbibed\_water}$$

$$v_{\text{PS}} = \frac{w}{c} - 0.23\alpha + 0.06\alpha = \frac{w}{c} - 0.17\alpha, \tag{10}$$

where all three terms on the right hand side of the equation have units of L/kg cement (assuming a specific gravity of 1.0 for water), for example, and represent the starting water, that bound during the hydration reactions, and that imbibed into the specimen due to the chemical shrinkage accompanying the hydration reactions, respectively. The coefficients 0.23 and 0.06 in Eq. (10) are generally accepted values [19] that could be modified based on measurements on a specific cement. While the bound water contents and chemical shrinkages accompanying the pozzolanic and hydraulic reactions of mineral admixtures are generally different from those of ordinary portland cement [18], here, as a first order approximation, Eq. (10) is applied to the total cementitious content of the concrete mixture with the degree of hydration, α, representing a mass-weighted average for the blended cement.

Using Eqs. (8)–(10) the potential moles of available alkali ions and the expected volume of pore solution (both per unit mass of cementitious binder) can be computed. A further complication that must be considered is the sorption of a fraction of these alkali ions by the cement hydration products. Taylor has considered this sorption in detail [20] and his "binding" factors have been employed in the version 3.0 CEMHYD3D cement hydration computer model [21] to compute pore solution composition, pH, and conductivity. Thus, the CEMHYD3D v3.0 model could be used to provide an estimate of the pore solution conductivity for a user-specified (blended) cement. In developing an alternative for use in the virtual test method, the following simplifying assumptions have been made, based on the detailed experimental results presented in Schafer and Meng [22]:

1. 75% of the potentially available potassium and sodium ions from the cement, silica fume, and fly ash are present in the pore solution at 28 d (the nominal age at which a RCPT is performed),
2. at this time, the alkali ions present in the slag are assumed to be contained in the slag hydration products and thus to have no influence on the pore solution composition; this is basically supported by the data of Schafer and Meng [22], and
3. as the silica fume content of the binder is increased, the 75% factor is reduced to a minimum value of 45% (achieved at silica fume contents of 15% and higher by mass fraction), to correlate with the strong absorption of alkali ions by the pozzolanic hydration products [20,22]. Using these assumptions and Eqs. (8)–(10), the concentrations of Na^+ and K^+ ions are computed. To maintain electroneutrality in the pore solution, the OH^- ion concentration is computed as the sum of these two cation concentrations.

Knowing the values of $[Na^+]$, $[K^+]$, and $[OH^-]$, the procedure developed by Snyder et al. [10] is then implemented to compute the pore solution electrical conductivity:

$$\sigma_{\mathrm{poresoln}} = \sum_i z_i c_i \lambda_i, \tag{11}$$

where z_i, c_i, and λ_i are the species valence, molar concentration, and equivalent conductivity, respectively. The equivalent conductivity is computed from [10]

$$\lambda_i = \frac{\lambda_i^0}{1 + G_i I_{\mathrm{M}}^{1/2}}. \tag{12}$$

Table 1
Equivalent conductivity at infinite dilution and conductivity coefficients for sodium, potassium, and hydroxide ions at 25 °C, from Ref. [10]

Species	λ^0 (cm^2 S/mol)	G (mol/L)$^{-1/2}$
Na^+	50.1	0.733
K^+	73.5	0.548
OH^-	198.0	0.353

The values of λ_i^0, the equivalent conductivity of an ionic species at infinite dilution, and the conductivity coefficient, G_i for Na^+, K^+, and OH^- are given in Table 1. The molar ionic strength, I_{M}, in turn is given by [10]

$$I_{\mathrm{M}} = \frac{1}{2}\sum_i z_i^2 c_i. \tag{13}$$

The above equations are implemented considering only the sodium, potassium, and hydroxide ions.

2.3. Temperature effects

Performing a simple energy balance on the testing configuration to account for the effects of Joule heating gives

$$\Delta T = \frac{Q_{\mathrm{gen}} - Q_{\mathrm{loss}}}{\sum_i m_i C_{\mathrm{p}}^i}, \tag{14}$$

where Q_{gen} and Q_{loss} represent the heat (energy) generated by the Joule heating of the testing configuration and that lost to the environment due to convection, respectively, and the denominator represents the "thermal mass" of the testing configuration, including the cylindrical concrete specimen, the two polymethylmethacrylate (PMMA) testing cells, and the solution that they contain (assumed to be 0.25 L per cell). For the virtual test, the following heat capacity values are employed: concrete −1000 J/(kg K) [23], PMMA −1470 J/(kg K) [24], and water −4180 J/(kg K) [25]. The heat generated during the test is simply given by the product of the applied voltage and the measured total charge passed during the test:

$$Q_{\mathrm{gen}} = V(\text{charge\_passed}). \tag{15}$$

Assuming the majority of the heat loss is due to convection to the local environment, the heat loss can be estimated using a convective heat transfer coefficient, h, and assuming a linear rise of temperature during the test [5]:

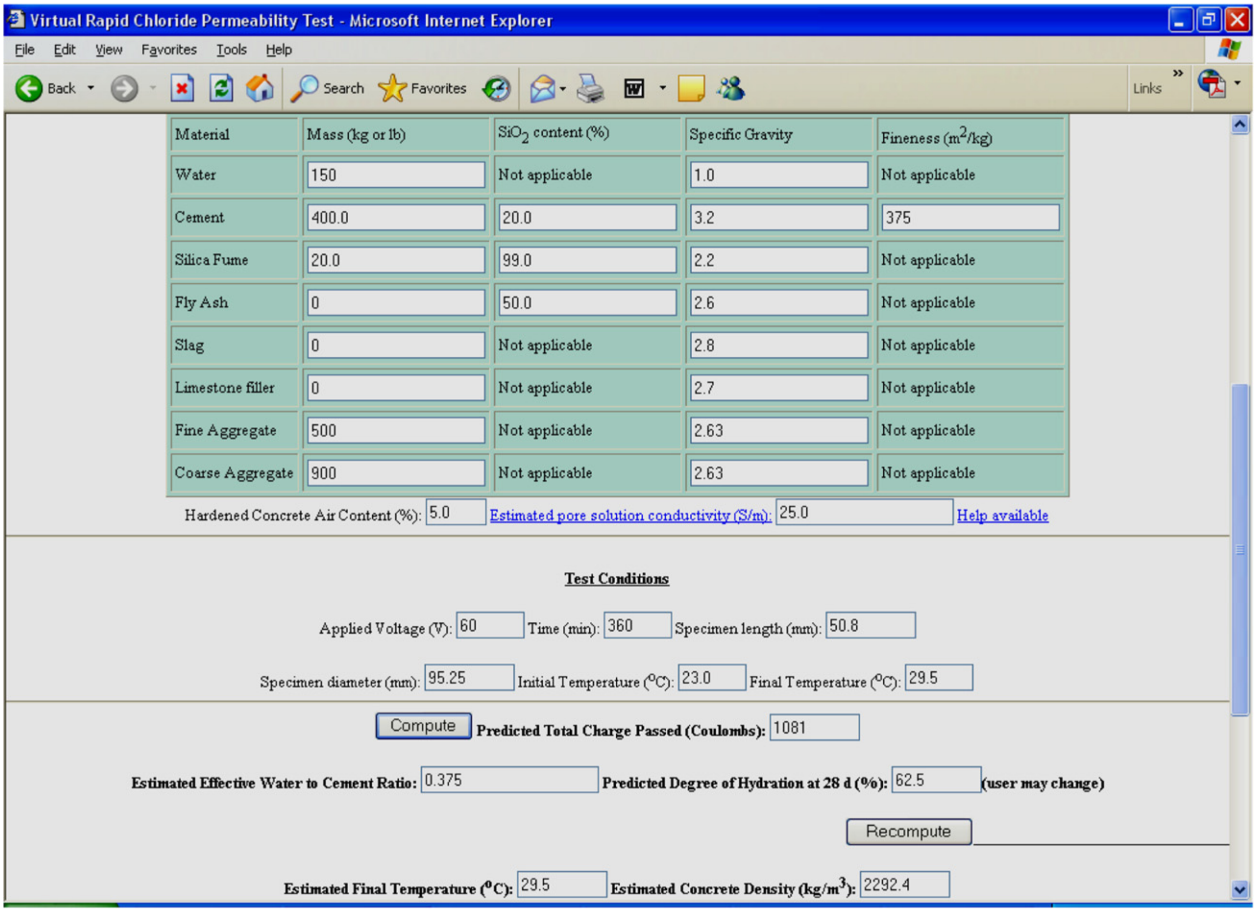
$$Q_{\mathrm{loss}} = \frac{hA_{\mathrm{test}}(\Delta T)t}{2}, \tag{16}$$

where A_{test} is the exposed surface area of the testing configuration and ΔT is the temperature rise experienced during the test. In the virtual test, it is assumed that the exposed surface area is given by the sum of the surface area of the exposed concrete specimen (total surface area − top and bottom surface areas), the surface areas of the two ends of the PMMA cells (6 in. by 6 in. (152 mm by 152 mm)), and the surface areas of six (3 × 2) sides of the PMMA cells (2 in. by 6 in. (51 mm by 152 mm), assuming that the fourth side of each cell will be resting on a lab bench and will provide a negligible contribution to the heat losses). While h will be a function of the temperature difference between the testing configuration and the local environment [25], here instead, a calibration against the experimental data presented by Feldman et al. [4] that will be presented later in this paper has resulted in the choice of h as a constant value of 4 W/(m^2 K), except for when the total charge passed is greater than 8000 °C and h is then increased to 6 W/(m^2 K). In the virtual test method, the user inputs the final temperature achieved in the test and the program returns an estimate of the final temperature calculated by the outlined procedure. The user may then manually iterate their input value for the final temperature until convergence is achieved or keep their original selection. For computing the total charge passed, it is assumed that the conductivity of the pore solution increases by 2% for each degree Celsius rise in temperature [5], in reasonable agreement with the measured initial and final currents and final temperatures of Feldman et al. [4].

2.4. Computer implementation

The above equations have been implemented in a set of forms-based HTML documents using the JavaScript script programming language. The top level of the virtual test method is available at http://ciks.cbt.nist.gov/VirtualRCPT.html. A separate document for estimating the electrical conductivity of the pore solution is available as a link from this top level or directly at http://ciks.cbt.nist.gov/poresolncalc.html. Because of the JavaScript implementation, all calculations are performed on the user's local machine. This also means that the user can simply save the HTML pages from their Internet browser to their local machine to have local access and/or make modifications to the underlying programs (coefficients, etc.). It is expected that as feedback is received from the user community, new features and improvements will be added to the prototype virtual test method.

Portions of the two main screens for estimating total charge passed and pore solution conductivity are provided in Figs. 1 and 2, respectively. Once the user provides all of the necessary information, the *Compute* button may be used to perform the virtual test.



Material	Mass (kg or lb)	SiO_2 content (%)	Specific Gravity	Fineness (m^2/kg)
Water	150	Not applicable	1.0	Not applicable
Cement	400.0	20.0	3.2	375
Silica Fume	20.0	99.0	2.2	Not applicable
Fly Ash	0	50.0	2.6	Not applicable
Slag	0	Not applicable	2.8	Not applicable
Limestone filler	0	Not applicable	2.7	Not applicable
Fine Aggregate	500	Not applicable	2.63	Not applicable
Coarse Aggregate	900	Not applicable	2.63	Not applicable

Hardened Concrete Air Content (%): 5.0 Estimated pore solution conductivity (S/m): 25.0 Help available

Test Conditions

Applied Voltage (V): 60 Time (min): 360 Specimen length (mm): 50.8

Specimen diameter (mm): 95.25 Initial Temperature (°C): 23.0 Final Temperature (°C): 29.5

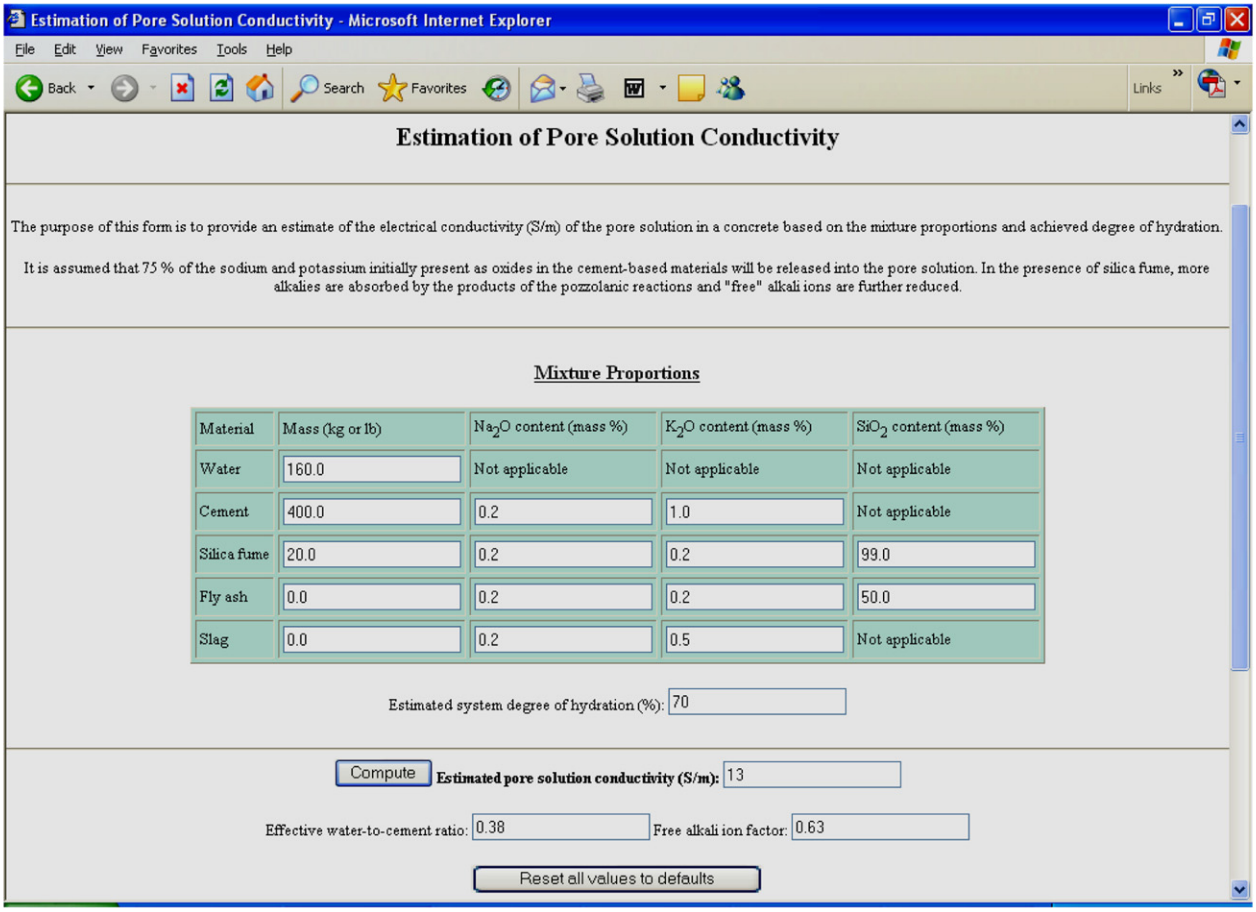
Compute **Predicted Total Charge Passed (Coulombs):** 1081

Estimated Effective Water to Cement Ratio: 0.375 **Predicted Degree of Hydration at 28 d (%):** 62.5 **(user may change)**

Recompute

Estimated Final Temperature (°C): 29.5 **Estimated Concrete Density (kg/m^3):** 2292.4

Fig. 1. Main page for estimating total charge passed during a virtual RCPT.



Estimation of Pore Solution Conductivity

The purpose of this form is to provide an estimate of the electrical conductivity (S/m) of the pore solution in a concrete based on the mixture proportions and achieved degree of hydration.

It is assumed that 75 % of the sodium and potassium initially present as oxides in the cement-based materials will be released into the pore solution. In the presence of silica fume, more alkalies are absorbed by the products of the pozzolanic reactions and "free" alkali ions are further reduced.

Mixture Proportions

Material	Mass (kg or lb)	Na_2O content (mass %)	K_2O content (mass %)	SiO_2 content (mass %)
Water	160.0	Not applicable	Not applicable	Not applicable
Cement	400.0	0.2	1.0	Not applicable
Silica fume	20.0	0.2	0.2	99.0
Fly ash	0.0	0.2	0.2	50.0
Slag	0.0	0.2	0.5	Not applicable

Estimated system degree of hydration (%): 70

Estimated pore solution conductivity (S/m): 13

Effective water-to-cement ratio: 0.38 Free alkali ion factor: 0.63

Fig. 2. Main page for estimating pore solution conductivity within the virtual RCPT.

3. Results

3.1. *Verification of the virtual test method*

Verification consists of determining that the virtual test method has been built *right* [26]. To determine that Eqs. (1)–(16) have been implemented correctly in the HTML pages, several steps were taken. The written codes were checked and double-checked to remove typographical errors, etc. While hand calculations could be performed to verify that the results produced by the virtual test method agree with those given in the above equations, in this case, the equations were implemented in a spreadsheet and the results of the virtual web-based test method were verified against the values provided by the spreadsheet(s).

3.2. *Validation of the virtual test method*

Validation consists of determining that the *right* virtual test method has been built [26]. The first part of the virtual test method to be validated was the computation of the estimated temperature rise during a C1202 test. A useful data set for preliminarily performing this validation has been provided by Feldman et al. [4], who measured the charge passed and the final testing configuration temperature for a concrete mixture that had been cured for different ages (1 week to 68 weeks), using four variants of the C1202 test method in which the testing solutions were varied (NaCl, NaOH, $Ca(OH)_2$). Their measured results, along with the predictions of the virtual test method are provided in Table 2. In most cases, the agreement between measured values and predicted ones is within 3 °C, which is considered to be an acceptable agreement.

Table 2
Measured and predicted final temperatures vs. measured charge passed based on measured data from Ref. [4]

Charge passed (C)	Measured final temperature (°C)	Predicted final temperature (°C)
13,100	85.7	86.1
7475	68.9	67.4
5130	56.0	53.5
2504	38.1	37.8
5726	59.1	57.0
2887	42.1	40.1
10,944	81.7	75.7
6729	66.1	63.0
4892	54.9	52.1
1773	34.5	33.5
3781	44.0	45.5
2118	29.4	35.6

The computation of the pore solution conductivity has not been validated beyond that performed in the original study by Snyder et al. [10], due to a lack of known experimental data sets. Thus, the validation proceeded directly to the values for total charge passed predicted by the virtual test method. Here, the experimental data sets of Simon et al. [27] and Feldman et al. [28] were employed. In the former, RCPT results have been reported for a series of 36 concrete mixtures prepared with various *w*/*c*, silica fume additions, and aggregate volume fractions, to demonstrate concrete mixture optimization using statistical mixture design methods [27]. In the quoted reference, no information is given on the oxide compositions of the starting materials, so that a pore solution conductivity of 25 S/m has been assumed for all of the concrete mixtures, due to their relatively low *w*/*c*. Furthermore, while the results reported in the reference are for a 42 d RCPT, the same degree of hydration function as given in Eq. (7) has been employed to predict the mixtures' degrees of hydration. A graph comparing the measured and "predicted" values for total charge passed for these 36 mixtures is provided in Fig. 3. On average, the predicted values are within 22% of the measured values, a reasonable agreement considering that a single value was assumed for the pore solution conductivity of all of the mixtures and that the quoted single-operator precision of the C1202 test method states that "two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by more than 42%" [2].

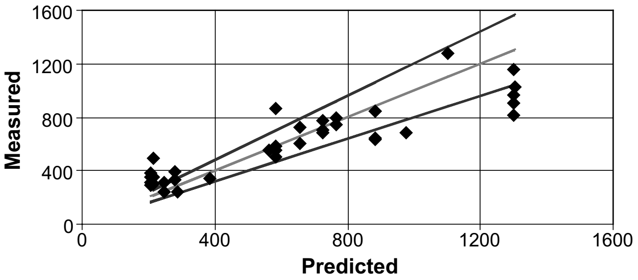


Fig. 3. Measured vs. predicted (virtual) RCPT results. Experimental data taken from Ref. [27]. Grey line indicates line of equality and dark lines indicate ±20% of the measured values.

The mixtures of Feldman et al. [28], were also utilized as input into the virtual test method. In this case, the alkali contents of the various binder materials were reported in the reference and were directly utilized in the HTML page for estimating pore solution conductivity. Lacking any specific information from the reference, an air content of zero was assumed and the degree of hydration was basically adjusted (as indicated in Table 3) to "calibrate" the virtual prediction to the experimental measurements. The obtained results are provided in Table 3 that indicates the mixtures evaluated, the age at testing, the measured RCPT total charge passed, and the predicted values for the pore solution conductivity, total charge passed, and final testing configuration temperature. The assumed degree of hydration has a significant influence on the predicted total charge

Table 3
Measured and predicted RCPT results based on measured data from Ref. [28]

Sample	Mixture proportions	Age (d)	Measured charge passed (C)	Predicted charge passed (C)	Estimated σ_{poresoln} (S/m)	Assumed degree of hydration of binder	Predicted final temperature (°C)
Shotcrete type I cem 7% fume (accelerator)	1:3.8:0.8:0.44[a]	150	1815	2030	9.6	0.72	35.0
Shotcrete type I cem 7% fume	1:3.8:0.8:0.44	150	1964	2030	9.6	0.72	35.0
Concrete type V cem	1:2.0:3.0:0.4	3	5378	5613	20.5	0.62	56.1
Concrete type V cem	1:2.0:3.0:0.4	28	2598	2815	21.6	0.72	39.6
Concrete type I cem	1:2.0:3.0:0.5	7	9682	9961	10.6	0.85	70.8
Concrete type I cem	1:2.0:3.0:0.5	56	5953	6002	10.8	0.89	58.5
Concrete type I cem	1:2.0:3.0:0.5	196	4328	3974	10.9	0.92	46.5
Concrete type I cem	1:2.0:3.0:0.5	476	1569	1705	11.3	0.99	33.1
Concrete type I cem 58% fly ash	1:2.0:3.0:0.32	28	663	608	35.8	0.58	26.6
Concrete type I cem 45% slag 3% fume	1:2.0:3.0:0.4	3	3552	3659	6.1	0.51	44.6
Concrete type I cem 45% slag 3% fume	1:2.0:3.0:0.4	28	522	556	6.8	0.7	26.3
Concrete type I cem 65% slag 3% fume	1:2.0:3.0:0.4	3	4405	2257	4.0	0.51	36.3
Concrete type I cem 65% slag 3% fume	1:2.0:3.0:0.4	28	356	359	4.4	0.7	25.1
Type I cem 75% slag 3% fume	1:2.0:3.0:0.4	3	3013	1527	2.8	0.51	32.0
Type I cem 75% slag 3% fume	1:2.0:3.0:0.4	28	262	253	3.1	0.7	24.5

[a] Mixture proportions: binder:fine aggregate:coarse aggregate: *w*/*c* as from [28].

passed in the virtual test, and while the values in Table 3 basically seem reasonable for the mixtures listed, this "calibration" is far from the ideal situation where the degree of hydration would have been measured using scanning electron microscopy [17] or other analytical techniques. Even with this calibration procedure, the data in Table 3 provides some interesting insights. For example, for the mixtures with the slag, the three predicted values for the 28 d RCPT are all within 7% of the corresponding experimental value, but the decrease seen with increasing slag contents is seen to be more an effect of a reduction in the pore solution conductivity than in the formation factor (assuming the same degree of hydration for all three systems). This highlights one of the known shortcomings of the RCPT, namely that the results are influenced both by the microstructure's formation factor (or transport coefficient) and by the electrical conductivity of the pore solution. This is mentioned specifically in the existing standard [2] with regards to the addition of calcium nitrate admixtures to the concrete mixtures. For the different mixtures in Table 3, the predicted pore solution conductivity is seen to vary over one order of magnitude; such variability would directly translate into one order of magnitude variation in the RCPT total charge passed. To give a specific example, a concrete with the same underlying microstructure and same inherent resistance to chloride ion penetration could exhibit an RCPT total charge passed of either 500 or 5000 depending on whether it contains a low-alkali or a high-alkali cement (itious binder).

4. Summary and prospectus

A first generation virtual RCPT has been presented and verified against several existing experimental data sets. Many engineering assumptions have been made in the development of this first generation virtual RCPT and it is thus seen as only a beginning in what will hopefully prove to be a fruitful path in the development of virtual standards for the cement and concrete community. A virtual standard is quite similar to a conventional standard but is based on a virtual measurement as opposed to a physical one [6]. It is emphasized once more that the software has been developed in such a manner that it is downloadable to each user's individual PC, where they are free to modify it and investigate variations/extensions as they see fit.

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