Case 1.5 PROOVE´it for Performance-Based Specifications by electrical methods, Summary

For sea structures and structures subjected to deicing salts ingress of chlorides into the concrete cover layer is by far the most important cause of their deterioration, resulting in billions of Dollars / Euros of annual maintenance costs. More severely, corrosion of steel ducts with strands/tendons penetration of chlorides may cause major damages and collapses when injection of the ducts has been done incompletely. Chlorides may also be present in the fresh concrete via the mixing water, contaminated aggregate, or chemical admixtures. More often, water-borne chlorides are carried into the pores of hardened concrete through forced gradients in chloride concentration, moisture content, temperature or pressure. The ease at which chlorides can flow into concrete is commonly referred to as "permeability" but, due to the different mechanisms of ingress, it should be better called "penetrability".

Building codes traditionally attempt to increase service life through prescriptive specifications that seek to improve chloride penetration resistance, depending on the exposure conditions, by requiring a minimum value of concrete compressive strength [f'_c] and a maximum w/cm ratio since both values are related to porosity. However, these limits are in fact very indirect because concrete's resistance to chloride penetration depends on only on the volume and number of pores but on the connectivity and tortuosity of their structure, as well as on the chemical composition of the pore solution. In the end, this lack of direct correlation makes specifications based on f'c and w/cm quite ineffective to limit chloride penetration into concrete. Instead, better tests are needed to try to directly measure the effects of the pore system and the complex chemical composition of the pore solution which in addition, suffer changes as concrete hydrates with its age.

Concrete ponding tests like ASTM C1543 and ASTM C1556 from which diffusion chloride coefficients can be obtained give a more precise approach but they are too expensive, labor intense and time consuming to be useful as practical performance tests.

Therefore, the best alternative so far are the "electrical tests" that indirectly provide a better measure of the pore network. One of the first and now the most popular method used for the purpose of measuring concrete electrical properties is the so-called **rapid chloride permeability test (RCPT) developed by Whiting and standardized as ASTM C1202**. It measures and integrates the current passed through a saturated concrete sample during a 6-hour period under 60 Volts DC. The result, given in coulombs, is used to classify the concrete's penetration resistance against chlorides, as shown in table 1. The term "permeability" has been informally widely adopted but is in fact not adequate for describing this test. Instead, the term "penetration" should be used.

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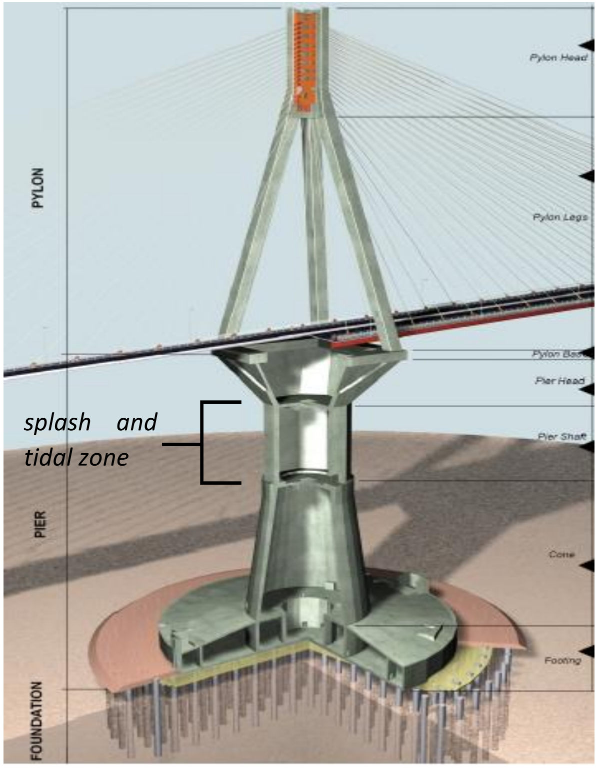
Table 1.

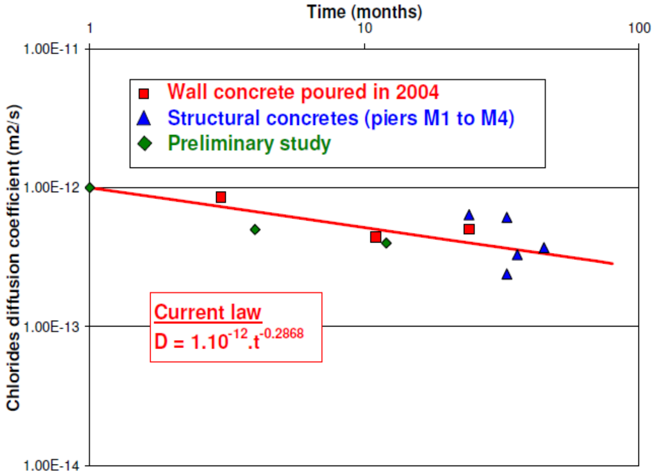
Charge passed, coulombs	Chloride ion penetrability
> 4,000	High
2,000 to 4,000	Moderate
1,000 to 2,000	Low
100 to 1,000	Very low
<100	Negligible

One good example about how this method can be used is the Rion-Antirion Bridge that crosses the Gulf of Corinth in Greece and has the longest cable-stayed suspended deck in the world. This engineering masterpiece, with a projected minimum service life of 120 years, had to overcome many difficulties including deep water, insecure materials for foundations, seismic activity, the probability of tsunamis, and strong winds. To ensure the long-term performance against chloride penetration and protect the reinforcing steel from corrosion, it was very important to properly characterized and evaluate the concrete. To optimize costs, the strategy consisted of a proper definition of different exposure zones to assign appropriate concrete cover layer thickness and concrete mixture performance. For instance, in the most critical exposure zone, the splash and tidal zone, identified as the zone between -5 m and +10 m from the medium see level, the requirement for the C45/55 class concrete used was a minimum nominal cover of 80 mm and a maximum RCPT value **of 1,000 coulombs at 90 days as the main durability indicator**, the same value that the Canadian CSA A23.1 standard specifies for reinforced concrete in chloride exposure where a long service life is required.



The selected concrete mixture was designed with a w/c ratio of 0.4 and contained low heat of hydration CEM type III and at least 60% of slag. The results reported from lab specimens and in-situ taken cores ranged between 350 and 500 coulombs and showed a perfect compliance and that transportation, cast, compaction and curing of the concrete were done correctly.

Simultaneously, some diffusion tests were performed to corroborate the RCPT results and together, they were used to build a mathematical model whose numerical simulations extrapolated the experimental data to verify that the desired 120 years of service life would be achieved. The model was later validated with results obtained after 24 months of construction.



Essentially, the RCPT, ASTM C1202, method uses the electrical conductivity of the concrete and its pore solution as an index of diffusivity. This follows the Nerst-Einstain relation:

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

Where applying for this case:

D = Diffusion coefficient of chloride ions in concrete

D_0 = Diffusion coefficient of chloride ions in the pore solution (assumed constant and equal to diffusion of chloride ions in bulk water)

σ = Bulk electrical conductivity of concrete

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σ_0 = Electrical conductivity of the pore solution

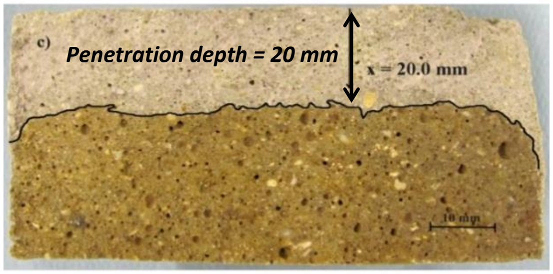
However, there are some concerns about it:

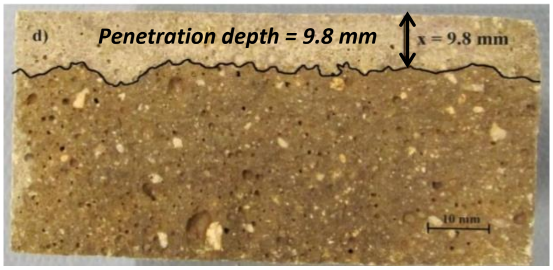
- Preparation and testing require 2 days
- The electrical conductivity over the long 6-hour test period under 60 volts can be affected by the Joule effect (ohmic heating).
- A direct correlation between RCPT values and diffusivity assumes that the ratio σ/σ_0 is constant. However, σ_0 relies on the chemical composition of the pore solution while σ does it also on the pore network structure. Assuming the ratio as a constant is just a rough approximation which could lead to significant errors. For instance, different proportions of supplementary cementitious materials can affect the pore solution chemistry much more significantly than the pore structure.

A simplified version of the RCPT for determination of **Bulk electrical conductivity and standardized by ASTM C1760** was developed to overcome these points. This test directly gives the value of σ, is easier to performed that the RCPT and eliminates the heating problem since it requires only a 1-minute period under 60 volts DC. Nevertheless, obtaining σ_0 is still difficult, and no practical method for routine use has been developed so far, but it can be estimated from the alkali composition of the cementitious binder as outlined by Snyder et al. (2003) and implemented as a free web application:

www.nist.gov/el/materials-and-structural-systems-division-73100/inorganic-materials-group-73103/estimation-pore

Here is where a third electrical method comes into play, **the Rapid Migration Test (RMT) developed by Tang and Neilson and standardized by Nordtest NT Build 492**. It operates under the same principle as the RCPT but is designed to drive chloride ions into the concrete specimen so that their depth of penetration can be measured.

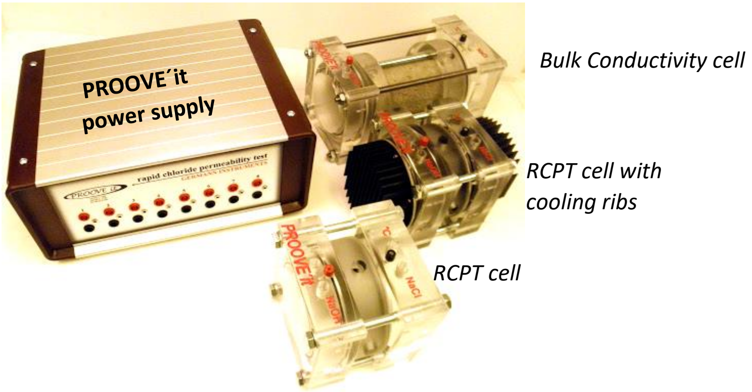




The applied voltage (10 to 60 volts DC) to accelerate the migration across the specimen and the testing time (6 to 96 hours) are set based on its initial conductivity so that the heating effect is minimized. At the end, the specimen is split in half and sprayed with silver nitrate solution to provide a visual indication of the depth of chloride penetration from which the so-called chloride migration coefficient is calculated. The RMT is also time-consuming but on the other hand, its results have been found to give lower variation than RCPT, not to be affected by the conductive ions in the pore solution and correlate better with diffusion coefficients obtained by ponding tests.

So, as the Rion-Antirion Bridge exemplifies, one of the best and most-effective means of extending the service life of reinforced concrete exposed to chlorides is the use of concrete with low penetrability, and performance-based specification can be easily adopted for this purpose by using any of the three available electrical test methods. They will provide better effectiveness than the commonly used strength and w/cm specifications.

But whatever electrical method is selected: the traditional Rapid Chloride RCPT by ASTM C1202, the Rapid Migration Test by NT Build 492 or the bulk conductivity test by ASTM C1760, the **Proove'it System** developed by German Instruments can perform all three by selecting the appropriate measuring cell. The power supply unit can deliver 5 to 60 volts DC for up to 8 measuring cells simultaneously while the current and temperature is registered automatically. The Proove'it system has been used for years by universities, research institutes, concrete and concrete admixtures producers as well as contractors in many challenging projects where long service life was required, and performance-based specifications have been used for accomplishing the objectives.



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