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Concrete Durability: Review of Rapid Chloride Permeability Testing For Durability Compliance

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ABSTRACT

This paper examines the applicability of the widely-adopted ASTM C1202-97 "Electrical indication of concrete's ability to resist chloride ion penetration", which is also AASHTO T277-83 "Rapid chloride permeability test" for the evaluation of the resistance of concrete to chloride ion penetrability. Particular reference is made to the first infrastructure project in Malaysia where the RCPT testing was specified for compliance.

The original correlation established using the AASHTO 90-day salt-ponding test, for ranking concretes in terms of their chloride ion penetrability using the RCPT results has various limitations. This is especially so for concretes incorporating chemical and mineral admixtures. This review attempts to develop a rational approach to a judgment on chloride penetrability of concretes. An overview of RCPT is made and possible alternative options for compliance testing considered.

KEYWORDS

Corrosion of reinforcement, Chlorides, Carbonation, Permeability, RCPT, Durable construction and Life cycle assessment.

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1 INTRODUCTION

The Butterworth Viaduct is a pre-stressed cable stayed road bridge and it was the first project in Malaysia where the RCPT test was specified as a requirement for concrete compliance (see JTK report r7026). The specification called for three types of concrete, OPC, OPC/PFA and OPC/PFA/SF. All exposed surfaces of the concrete were to be coated with an anti-carbonation coating. Three of the piers are within the tidal estuary and hence exposed to chlorides via splash or direct contact. The rest of the structure is exposed to wind borne chlorides.

Considering the importance placed on achieving long term durability, there was no specified design life (intended working life – BS 8500-1, 2006), or a definition of what constitutes the end of the service life.

2 EXPOSURE CONDITIONS

2.1 Marine Exposure Conditions

Deterioration of marine concrete structures is mainly due to the ingress of chloride ions into the concrete, leading to corrosion of the embedded steel reinforcement. This potentially leads to a shortening of the service life and increasing the maintenance costs of these concrete structures. Durability of such structures is a particular concern in the hot wet tropical environment in Malaysia and the use of low permeability concretes is key method adopted in ensuring serviceability.

As the bridge was to be built over a tidal estuary it can be safely assumed that the structure will be exposed to chlorides. The exposure regimes can be divided into areas where wind borne chlorides will predominate, a splash zone area, a tidal zone and a submerged area below the low water tide level (exposure classes, XS1, XS2 and XS3 – BS EN 206-1: 2000).

2.2 Carbonation

The carbonation process is very susceptible to moisture content of the concrete. Either side of 65% RH the carbonation rate diminishes rapidly. Thus in areas where the concrete is saturated, such as below ground or water, carbonation is not a concern (exposure classes, XC1, XC2, XC3 and XC4 – BS EN 206-1: 2000).

At higher levels, above the splash zone, the threat of carbonation will be greater. However with the type of concrete provided (Grade 60) and particularly as the segments are required by specification to be well cured, carbonation was not thought to be a durability issue of concern. To add to this the application of an anti-carbonation coating as required by the contract will improve the resistance of the concrete.

2.3 Chloride Ion Resistance Testing

2.3.1 Background

Steel in concrete is normally stable due to the formation of a passive iron oxide film on the steel surface. Corrosion initiation due to the presence of chloride ions is thought to be the primary mechanism leading to a loss of durability over time. Once chloride ions reach a critical concentration at the reinforcement surface, the passive iron oxide film breaks down and corrosion is initiated.

One of the aspects to consider during the design of a reinforced concrete structure for a service environment where chloride ions are present is therefore the chloride ion (CI) resistance of the concrete. This can be utilized to determine the maintenance free period with respect to corrosion. Similarly, for the repair and/or protection of a chloride contaminated structure (or structure in a chloride environment) the CI resistance of the repair materials and surface coating/penetrant systems is a very important performance parameter.

Chloride ion diffusion, penetration and permeability tests have therefore been developed so as to establish the Cl resistance of concretes, cementitious/polymeric repair materials and surface coating/penetrant systems.

2.3.2 Test Methods

Various durability tests have been developed for the evaluation of the resistance of concretes to chloride ion penetration. The tests can be broadly grouped into ponding/immersion/salt spray tests, concentration driven diffusion tests and voltage driven accelerated diffusion/permeability tests. These tests include long-term soaking tests such as the AASHTO T259 "90-day salt-ponding test" which aims to simulate the actual marine exposure environment and rapid tests such as the ASTM C1202-97 "Electrical indication of concrete's ability to resist chloride ion penetration", generally known as the rapid chloride permeability test (RCPT).

Environmental chloride contamination of concrete structures occurs via the following transport mechanisms:

Diffusion, associated with Cl concentration gradients (eg. tidal and atmospheric zones of a marine structure).

Dispersion and diffusion. Dispersion of Cl takes place when bulk flow of saline water occurs, eg. water sorptivity. The splash zone of a marine structure is an example of where dispersion (ie. high surface build-up of C1 occurs due to absorption of water borne chlorides) and diffusion of C1 occurs.

Hydrostatic pressure gradient (eg. water borne chloride transport in the submerged zone of a marine structure).

The ponding, immersion, concentration driven diffusion and voltage driven diffusion tests enable determination of Cl diffusion resistance (via measurement of a Cl diffusion coefficient).

The voltage driven diffusion methods were developed because of the sometimes impractical test duration (i.e. months to years) of the concentration driven methods. The conventional long-term soaking tests take a long time, resulting in the increasing usage of the RCPT as a rapid means of assessing concrete permeability.

Neither a Cl diffusion or penetration coefficient is obtainable from the ASTM C 1202-97/AASHTO T 277-831 rapid permeability test. The total charge passed, in coulombs, determined from this test is related to chloride ion penetration resistance. A Table of Charge Passed versus Chloride Ion Penetrability is provided in the standards where Cl penetrability is stated qualitatively as either "negligible", "very low", "low", "moderate" or "high".

In essence, the RCPT measures the total amount of charge (in coulombs) that passes through a standard cylindrical test specimen during the test duration of 6 hours. Based on the total amount of charge passed, the concrete is given a chloride ion penetrability ranking using the general correlation (Table 1) in ASTM C1202 (1997) established by Whiting (1981) using the 90-day salt ponding test.

Table 1. Chloride ion penetrability based on charge passed.

Charge Passed (Coulombs)	Chloride Ion Penetrability	Type of Concrete
> 4,000	High	High W/C
2,000 to 4,000	Moderate	0.4-0.5 W/C
1,000 to 2,000	Low	W/C < 0.4
100 to 1,000	Very Low	Latex modified Concrete
< 100	Negligible	Polymer concrete

Note: W/C = water-cement ratio

Limitations

Critical aspects related to the in-service chloride ion resistance of a concrete mix include:

i) chloride binding capacity of a cementitious binder
ii) tendency towards development of a high surface chloride build up of a cementitious binder
iii) pore size, continuity and tortuosity of the cementitious paste
iv) threshold chloride content of a cementitious binder type to initiate reinforcement corrosion

The ASTM C 1202-97/AASHTO T 277-831 rapid Cl permeability test provides only an indication of aspect iii). In fact, the widely-adopted RCPT has been criticized by many researchers to be non-reflective of concrete permeability. The test is based on the principle that the electrical resistivity of concrete decreases with increasing free chloride ion concentration. As such, this test would reflect the electrical resistivity of the concrete being tested rather than the resistance of the concrete to chloride ion penetration (Wee et al 1999) (3). The electrical resistivity of concrete is affected by the paste volume of the concrete (Wee et al 1999) and the chemistry of the pore solution (Buenfeld and Newman 1987) (3). Arup et al (3) already stated in 1993 that “the information provided by a rapid chloride permeability test or an ASTM C 1202-97/AASHTO T 277-831 test is – at the most – equivalent to that which can be obtained by measuring the resistivity of the water –saturated sample and can not be taken as measure of C1 diffusion resistance, unless the conductivity of the porewater in that particular type of concrete and in that particular hydration state is known and the appropriate correction made.” Andrade (1993) also confirmed that the total amount of charge passed during the test accounts for the total current due to the flow of all the different ions present in the electrolyte solution of the concrete and not only that corresponding to the flow of chloride ions further adding to the uncertainty of the result.

The scope of ASTM C 1202-97 state that this method is applicable to concretes in which a correlation has been established between the coulomb value and long term Cl ponding tests such as AASHTO T 259-80. Pfeifer et al (4) stated that “based on the documents referenced in ASTM C 1202, it is concluded that reliable and proper correlations do not exist between the rapid test procedure results and 90-day ponding test results. The ASTM C 1202 or AASHTO T 277 test procedures should not be used in specifications without proper correlation to long term tests. It is recommended that the table relating chloride penetration to coulomb values in these test procedures be removed since it is inaccurate and can be misleading”.

Pfeifer et al (4) also stated that “selection or rejection of concrete based solely on ASTM C 1202 can result in improper decisions and the rejection of concrete known to be durable”.

“The studies reviewed show that virtually impermeable conventional concretes can be produced with very low water-cement ratios of 0.30 to 0.32, even though their coulomb values may range from 1000 to 5000”.

It is clear that a wide school of research and study has come to the conclusion that while a useful tool the usage of RCPT as a sole test for durability compliance is not advisable.

3 REVIEW OF AVAILABLE DATA

3.1 Overview of Approach

As part of the compliance requirements beam elements of size 750 x 150 x150 were prepared by the concrete supplier at the time of casting and cured either at the pre-cast yard or at a designated Laboratory. Four (4) beams were cast for every segment. These were cured prior to testing as follows:

As soon as the beam is cast, concure was sprayed on the open face followed by a 50 mm saturated foam. Over this a saturated hessian was laid which was kept moist by a water drip system. Demoulding took place between 14 and 24 hours and the samples were immediately stored in a water bath until testing. Cores were taken from the beam samples at the designated test ages (28, 60 or 90 days) and the samples subjected to the RCP test. The compliance criteria according to the contract are summarized in the table below. An allowance for further testing at 90 days is provided for if the 60 day results are 500 to 575 coulombs and 1000 to 1150 coulombs for the pre-cast and in-situ elements respectively.

Table 2. RCPT Compliance Criteria.

Element Type	Compliance Criteria	Maximum Coulombs at 28 Days	Maximum Coulombs at 60 Days	Maximum Coulombs at 90 Days
Pre-cast Elements	Primary Compliance	575	500	
Pre-cast Elements	Further Testing Permitted at 90 Days if 60 day result >575		500 - 575	500
In-situ Elements	Primary Compliance	1150	1000	
In-situ Elements	Further Testing Permitted at 90 Days if 60 day result >1150		1000 - 1150	1000

It should be noted that these compliance requirements are onerous and do not allow for any measurement uncertainty which is inherent in the RCP test. The specified value, e.g. 1000 Coulombs may be treated as the characteristic value. Assuming 30 % expected variability of test results as the margin, the target value is therefore 700 and an extreme value of 1300 accepted as the uppermost limit with not be more that 5 % above 1000. The precision statements in ASTM C1202-97 in fact states that "the single operator coefficient of variation is 12.3% indicating that the results of two properly conducted tests by the same operator on concrete samples from the same batch and of the same diameter should not differ by 42%.

3.2 Concrete Segment details

The concrete mix supplied for this project is summarised below:

Table 3. Concrete mix design details.

	Precast	In-Situ
Mix Type	TM14	TM4
OPC (kg/m3)	210	270
Masscrete (kg/m3)	270	180

Silica Fume (kg/m3)	38.5	27
20 mm Aggregates (kg)	1000	1040
Sand (Kg)	650	755
Water content (Liters)	145	150
Daracem liters per 100 kg cement	9.12	9.06
Daratard 40 liters per 100 kg cement	1.20	1.24
PFA %	14	10
Silica Fume %	8	6
W/C Ratio	0.280	0.314
RCP Criteria (Coulombs)	500	1000
Trial RCPT	488, 491 (At 40 Days)	741, 759 (At 36 Days)

Approximately four segments were cast per day at the pre-cast yard with concrete volume per segment varying from 31 cu m to 50 cu m. The cover to reinforcement is as low as 26 mm for the pre-cast elements and 45 mm for the in situ elements.

3.3 Review of Results

The RCPT results are summarized below and based on this the project consultants deemed the concrete to be non-compliant. The results are presented sequentially for concrete cast between 12 Jan 2002 to 17 Nov 2002. RCPT results at 28 days were available up to 21 Sept 2002. The equivalent data at 56 days and 90 Days were available up to 26 Aug 2002 and 3 Aug 2002 respectively.

There is quite a variation in the RCP results particularly at 28 days. However the coefficient of variation of results at all ages is less than 30%. In general as concrete hydrates there would have been an expected decrease in permeability and resistivity of concrete but there are several instances (5 out of 41 results) when the RCPT results in fact increase in value between 56 and 90 days. This is also reflected in the higher mean results. It should however be noted that the ASTM C1202-97 standard concludes that the results of 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%. These results should therefore be viewed in the light of the fact that they are within the expected variability of individual test results and may not represent a real increase in permeability at all. It was the view of the author that rejection of the concrete purely based on the RCPT tests without taking into consideration the variability of the test itself was not defensible

Table 4. Summary of RCP results for the precast concrete (TM14).

TM14	28D Strength	56 D Strength	28 RCP	56RCP	90 Day RCP
Max	88.2	88.2	1149	830	803
Min	61.9	68.5	353	219	367
No	357	160	153	134	41
Mean	76.1	79.0	638	496	512
Std Dev	4.3	4.5	182	111	91
COV	5.6	5.7	28	22	18

4 COMPLIANCE TESTING

The original development of the RCP test in 1981 was based on a correlation to the 90–day ponding test. Several researchers have examined this further and found that the correlation between the tests rather less convincing particularly with modern concretes with additives. Pfeifer et al. (1994) for example found that they obtained inconsistent test results when comparing the salt ponding test and the RCPT procedure. McGrath and Hooton (1999) also found that due to the partially saturated condition of the ponding test specimens, other processes such as wicking, adsorption and carbonation are involved and these effects are difficult to account for in a laboratory environment. Furthermore, the methods of analysis of the 90-day salt ponding test data are all based on apparent diffusion, which is a factor derived from the actual penetration. It should also be noted that the original tests were undertaken primarily for OPC concretes and polymer modified concrete. These reasons probably account for the difficulties encountered by researchers when trying to reproduce the linear relationship between the results generated from the RCPT and the 90-day salt ponding test (Goh et al, 2002). Scanlon and Sherman (1996) also reported a substantial conflict between the two test procedures and stated that the generalized relationship found by Whiting was not valid if silica fume, fly ash, blast furnace slag or superplasticizer was used. It should however be noted that some of these variations are associated with the general variability of the test itself and the associated variability of concrete.

As noted above the classification of the chloride ion penetrability of concrete based on the RCPT results and the chloride ion penetrability rankings set forth in ASTM C1202-97 specifications was originally based on the ponding test (ASSHTO-T227).. This test is not meant to provide a correlation to RCPT as it is already well established that any such relationship is difficult to establish even in controlled laboratory trials. The ASSHTO test should be used merely to check on the variability of concrete from a penetrability point of view.

5 CONCLUSIONS AND RECOMMENDATION

The ASTM C 1202-97 rapid chloride permeability test (RCPT) is a durability tests based on voltage driven diffusion which has been developed for the evaluation of the resistance of concretes to chloride ion penetration. Voltage driven methods were developed because of the sometimes impractical test duration (i.e. months to years) of the concentration driven methods. This test has often been specified as the primary compliance requirement for concrete durability.

A wide school of research and study over several years has come to the conclusion that while a useful tool, the usage of RCPT as a sole test for durability compliance is not advisable. The test provides an indication of pore size, continuity and tortuosity of the cementitious paste and more a measure of electrical resistivity rather than the resistance of the concrete to chloride ion penetration.

Despite the concerns for durability which were apparently raised based solely on the RCPT results it was the opinion of the Author that given the concrete of mix design and the triple blend OPC/PFA/SF concrete specified and the consistent achievement of normal quality control parameters and the fact that additional coatings were applied to the structure any concerns for durability based solely on 'non-compliance' to RCPT requirements in this contract were unfounded.

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