Validation of service life performance of in situ concrete by TEM and RCM measurements

M.R. de Rooij

Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, The Netherlands & TNO Built Environment and Geosciences, Delft, The Netherlands

R.B. Polder

TNO Built Environment and Geosciences, Delft, The Netherlands

H.H. van Oosten

Engineering firm Movares, Utrecht, The Netherlands & Ministry of Transport and Watermanagement, Zoetermeer, The Netherlands

Nowadays important concrete infrastructure is increasingly being designed for long service life by probabilistic assessment of uncertainties, e.g. using the DuraCrete method. Although on paper a reliable and durable structure will result, it is the execution phase that can make or break the service life. Hence, testing the concrete for its durability during the actual production is necessary.

This paper presents a study of non-destructive production control testing and service life achievement of cast in situ parts of the Green Heart Tunnel. Production control was performed by resistivity measurements using the Two Electrode Method (TEM). Validation consisted of measurements on cores taken after one to three years on site, which were tested using the Rapid Chloride Migration method. The results show that quality control by resistivity testing as carried out in this project was successful.

Key words: Rapid chloride migration, service life design, two electrode method, durability

1 Introduction

The concept of reliability based service life design of concrete structures dates back to the 1980s [Siemes, 1985]. Since the completion of DuraCrete [DuraCrete, 2000], a practical methodology is available which is now internationally implemented in the codes [*fib*, 2006]. Important concrete infrastructure is increasingly being designed for long service life. Service life calculations in the design phase are necessarily based on modelling of degradation processes and testing of trial concrete mixes. On paper a reliable and durable structure can result, while it is actually in the execution phase that the service life of a structure is realized. Thus, during the execution phase some form of testing for durability of the concrete from the actual production is needed. However, the tests that are used to determine the durability properties during the design phase as e.g. the Rapid Chloride Migration (RCM) test, are too slow and too expensive for application during the execution phase. In the production phase faster, cheaper and preferably non-destructive tests are favoured to check on durability.

This paper presents a validation study of a non-destructive test method for durability properties of concrete during production. This so called Two Electrode Method (TEM) is based on resistivity principles.

2 Green Heart Tunnel and its service life design

The Green Heart Tunnel (GHT) is a bored concrete tunnel half way between Rotterdam and Amsterdam in the High Speed train Link (HSL) between Amsterdam and Brussels. It has a length of about 8.6 km, with the main tunnel constructed by boring a single tube of 14 m inner diameter, with a lining of precast concrete segments. The ramps, sidewalls, rail beds, safety kerbs and the center wall as well as three ventilator shafts and two technical buildings were cast in situ. Fig. 1 provides a longitudinal as well as a transverse cross section. The tunnel runs approximately North-South.

The client, Project Organisatie HSL, required a technical service life of 100 years for the Green Heart Tunnel, to be demonstrated by a (quantitative) service life assessment. All known deterioration mechanisms had to be considered, including ASR and reinforcement corrosion due to carbonation and chloride ingress. Chloride exposure had to be based on seawater, considering possible leakage of ground water, which is presently brackish but in the future may become more saline.

The demonstration part of the technical service life during the design phase is not part of this paper. However, for the remainder of the paper it is useful to refresh certain principles. A service life demand of 100 years by itself has no meaning, because it does not describe what the structure still should be capable of after 100 years: should it just still be there, but its use is to the personal risk of the traveller, or should it be capable of handling twice the amount of weight of a loaded freight train from what it was originally designed for? In short, we need to agree on limit states. How much carbon dioxide or chloride is allowed near the outer reinforcement, for instance, when we are considering corrosion? Once we have these limit states we have something to design for and to check on.

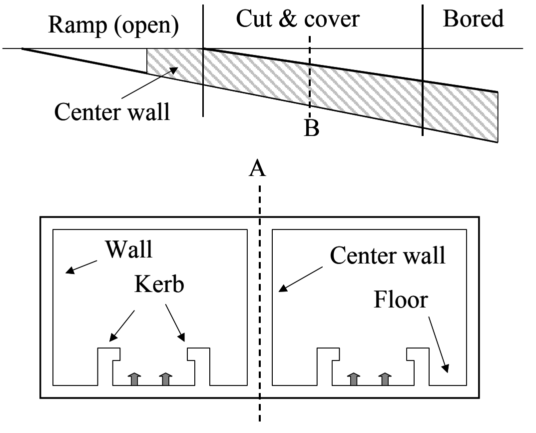

Figure 1: Green Heart Tunnel, schematic longitudinal cross section of Ramp, Cut & Cover part and Bored tunnel (top) and schematic transverse cross section with center wall, kerbs, floor and wall inside the cut & cover part (bottom)

Next important point in a service life assessment is the necessity of models. Since we are considering something in the future, we need models that can predict that future for us. Naturally the models should be correct, but unfortunately our current knowledge level is not capable of explaining all phenomena in all their details and complexity. Upon increasing our knowledge on e.g. degradation processes, it will be sure that our models will improve during the service life of a structure. The best thing at the moment is to agree on the use of certain models in the design phase and use these models to validate the durability of the structure.

These steps have all been followed in the assessment of the Green Hart Tunnel. Limit states were set in two ranges: for the ultimate limit state (ULS) the reliability index was set at 3.8; for the serviceability limit state (SLS) the reliability index was set at 1.8. Using DuraCrete and its state-of-the-art degradation models specific requirements could be derived from the structural design concept. This resulted in: a minimum chloride diffusivity of $5*10^{-12}$ m^2/s, to be tested using the RCM method at 28 days [NT Build 492, 1999]; a minimum

cover depth of 45 mm (35 mm in kerbs, 50 mm if non-inspectable); and the in-situ concrete should be made with blast furnace slag cement with a high slag content, CEM III/B.
On the basis of these requirements trial mixes were made in order to check the concrete properties for a.o. diffusivity. The contractor, Bouygues-Koop (B/K), asked TNO to assist in meeting these requirements. Several mixes were found to produce RCM values between 3 and 4 $*10^{-12}$ m^2/s at 28 days. The final mixes that have been used were based on 360 to 400 kg CEM III/B LH HS (blast furnace slag cement with c. 75% slag) per cubic meter, a w/c ratio of 0.44 and maximum aggregate size of 32 mm.
Although it had been shown in the design phase that the chosen concrete mixtures could be made with an RCM-value below the maximum specified value (here $5*10^{-12}$ m^2/s), in the production phase the contractor needed to make sure this was indeed maintained. Based on a general correlation between inverse resistivity and chloride transport in concrete [DuraCrete, 2000; Polder, 1997], B/K proposed to test the quality of day-to-day production concrete with regard to durability by measuring its electrical resistivity using a method known as Two Electrode Method (TEM) [DuraCrete, 2000; Polder, 2001]. TEM testing would be performed on the control cubes made at the production site for 28 days strength verification, hydrated under water. The general correlation between inverse TEM and RCM is illustrated in Fig. 2 for a range of concrete mixes (including various binders) at a range of ages, tested at TNO. Various literature sources provide similar correlations [DuraCrete, 2000; Gehlen, 2000].
Through this correlation a minimum value for TEM has been deduced, that relates to the maximum allowed value for RCM. In this correlation also the coefficient of variance (COV) in the TEM results is taken into account. In other words, the production of a consistently high quality of concrete is rewarded by accepting a lower minimum TEM value. As a final safety measure in terms of durability, the contractor aimed at producing concrete with a maximum 28 days RCM-value of $3.5*10^{-12}$ m^2/s. This relates to minimum target values for TEM of 260 Ωm when the COV is 0.1, while it should be at least 360 Ωm when COV increases to 0.3, to give some indications.

3 Measuring, sampling and testing

A volume of 30,000 to 40,000 m^3 cast in situ concrete was produced between the years 2000 and 2004 in two on-site mixing plants, over a total of about 1000 production days. During that long production period and over the locations where the concrete was used, various factors may have caused variation of concrete quality: cement content, temperature (season), curing and exposure (to solar radiation and rain). The client, Project Organisatie HSL-Zuid, and their quality auditor, C.S.O. Adviesbureau, asked the assistance of TNO for the validation of the TEM quality control of the in-situ concrete with regard to durability. The client first randomly selected a number of day productions. Then, out of the various parts cast from those day productions, eight test areas (TA) were selected for investigation as described in Table 1, in order to have a wide variation of the factors mentioned, that could influence the final durability of the concrete. Each Test Area comprised 2 x 2 to 2 x 4 m^2 of concrete surface.

In each TA, about 60 reinforcing bars were located and their cover depth measured using a HILTI Ferroscan FS10 scanning cover meter. Furthermore, from each TA 12 cores (∅ 100 mm, L = 250 mm) have been taken to provide specimens for compressive strength testing according to NEN-EN 12390-3, as well as specimens for RCM testing. Per TA six specimens are tested for compressive strength, generally from a depth of 100 – 200 mm. Per TA, 12 specimens were tested for RCM according to NTBuild 492. Due to the presence of considerable amounts of reinforcement it was impossible to obtain sufficient specimens from the outer concrete without rebars. Consequently limited number of RCM specimens were tested from the outer layers including the surface (0-50 mm), but RCM specimens originated in general from 50 to 100 mm depth, with some from 100-150 mm or 150-200 mm.

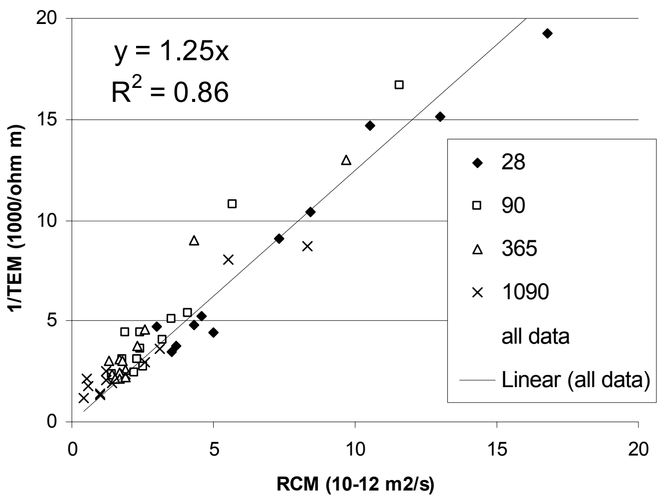

Figure 2: General correlation between inverse resistivity (by TEM) and chloride diffusivity (by RCM) for various binders at various ages (indicated in days) as tested at TNO

Table 1: Test Areas for cover depth measurements and concrete sampling

Test Area	Object	Type
1	South Ramp	Center wall
2	South Cut & Cover	Center wall
3	South Technical Building	Basement Wall AC
4	Shaft Bent	Level +1, East Wall P
5	Tunnel N11	East Inner Kerb
6	Shaft Achthoven	Level +0 Wall C
7	North Cut & Cover	East wall
8	North Open Ramp	Floor

RCM values were calculated back to 28 days values using the DuraCrete time-dependent model for diffusivity. B/K's Concrete Sample Test Reports (CSTR) of TEM results on the concrete used for the TA's were provided to TNO for the validation procedure.

Table 2: Cover depth measurement results in eight Test Areas (number of bars c. 60 per TA)

Test Area	Object	Mean (mm)	Standard deviation (mm)	Minimum (mm)
1	South Ramp/ Center wall	48	16	5 *
2a	South Cut & Cover/ Center wall	67	5	57
2b		59	9	42 @
3a	South Technical Building /Wall	57	4	47
3b		61	7	46
4a	Shaft Bent /Wall	45	7	32 $
4b		71	11	52
5	Tunnel N11 /Kerb	49	9	36
6a	Shaft Achthoven /Wall	45	12	25 #
6b		76	9	52
7	North Cut & Cover /Wall	81	8	66
8a	North Open Ramp /Floor	69	9	49
8b		70	5	58

* *19 bars < 45 mm out of 63 measured (4 bars < 15 mm)*

@ *one bar < 45 mm*

$ *2 bars < 35 mm, 16 bars < 45 mm, out of 34 in TA 4a*

\# *5 bars < 30 mm, 16 bars < 45, out of 32 bars in TA 6a*

4 Results

Results of cover depth measurements are reported in Table 2; in some cases the TA was divided in sub-units for practical reasons, like a doorway in the middle of the TA or a TA of two wall parts.

Additional cover depth measurements were taken in the South Ramp/center wall by the client. They measured for a total of 48 bars, distributed over 4 parts and taken from both sides of the center wall, cover depths in the range from 30 to 80 mm.

Results of RCM testing for specimens from the inner concrete (50 – 200 mm depth) are reported in Table 3. Data on RCM tests of the outer layers of the concrete (0 – 50 mm depth) are shown in Table 4. TEM results for concrete used in the TA's taken from CSTR as measured during production are reported in Table 5.

5 Discussion

5.1 Cover depths

The results of the cover depth measurements as presented in Table 2 should be judged against the requirements for these TA's. For all TA's with the exception of TA 5, this means the minimum cover depth should be 45 mm. In TA 5, a kerb in the tunnel, the minimum cover depth should be 35 mm.

Table 3: Mean and standard deviation of RCM of cores from Test Areas (n=12 per Test Area), inner concrete (50 – 200 mm depth)

Test Area	**RCM, mean (* 10^{-12} m^2/s)**	**RCM, standard deviation (* 10^{-12} m^2/s)**	**Age (year)**
1	2.00	0.86	1.17
2	2.73	1.54	1.00
3	2.76	1.17	1.25
4	2.01	0.86	1.17
5	1.82	0.65	1.75
6	1.20	0.56	2.08
7	1.29	0.54	3.25
8	1.27	0.34	1.50

Based on the mean values of the cover depth, one could say on the positive side that the mean is 45 mm or more and that the reinforcement in general is located at considerable depth inside the concrete. However, also taking into account the large scatter of about 15% (COV) with two locations even going to 30%, a more detailed discussion seems appropriate.
As minimum cover depth does mean minimum cover depth, only TA's 3, 5, 7 and 8 comply with this requirement. TA number 2 almost complies to the requirement: of all the rebars measured in TA 2 only one was below 45 mm, with an actual cover depth of 42 mm. Assuming a normal distribution for the cover depth values, the client reasoned that one rebar was an acceptable, insignificant accident.
For TA's 1, 4 and 6 the results of the cover depth measurements were not acceptable from a durability point of view based on exposure to chloride. Hence, for these TA's a further

Table 4: RCM of specimens taken from the outer layers of the concrete (0 – 50 mm), n = 3 per TA

Test Area	**RCM, mean (* 10^{-12} m²/s)**	**RCM, standard deviation (* 10^{-12} m²/s)**	**Age (year)**
1	2.55	0.71	1.17
2	2.50	0.16	1.00
6	2.25	0.28	2.08
7	1.86	0.54	3.25
8	1.58	0.80	1.50

Table 5: TEM results at 28 days age for concrete used in the TA, measured during production

Test Area	**Concrete Code**	**TEM results (Ω.m)**										**μ_{TEM} (Ω.m)**	**σ_{TEM} (Ω.m)**
1	B35 IS 5D	376	355									366	15
2	B35 IS 5D	375	381	414	414	410	422					403	20
3	B35 IS 5D	279	285									282	4
4	B35 IS 5D	348	373	340	340							350	16
5	B35 IS 5E	478	443									461	25
6	B35 IS 5D	266	283									275	12
7	B35IS Ramp	327	339	366	352	395	364	366	351			358	20
8	B35 IS 5D	351	323	317	324	332	357	313	313	312	308	325	17

analysis was made. TA's 4 and 6 are inner walls of the shaft buildings. TA 1 is the outer part of the center wall, open to wind and rain. For all three of these TA's exposure to chloride from ground water leakage is highly improbable. Consequently, these TA's do not have to be validated against chloride load; in these cases carbonation of concrete becomes service life determining. New probabilistic calculations were made using TNO's software package Prob2B™ (formerly PROBOX), based on carbonation related input from the original SLD according to DuraCrete [DuraCrete, 2000].

The calculations showed that for the concrete used, at t = 100 year cover depths of 35 mm resulted in a reliability index β well over 1.8 for the absence of corrosion initiation due to carbonation; actual values were at least 2.6. For the shafts a cover depth of 20 mm just complied (β=1.8); this is thought reasonable for sheltered concrete. For the center wall (which is exposed to wetting by rain) calculations showed that 8 mm of cover depth would suffice. However, for this latter case we know from practical experience that this is not correct: such low cover depths give a high probability of corrosion and subsequent damage in the form of cracking and spalling. It appears that the DuraCrete carbonation model contains simplifications that are not correct for such low cover depth values. Based on practical experience a minimum of 20 mm seems more appropriate.

Summarising, cover depths of 20 mm and more are viewed as acceptable if chloride ingress can be excluded. Accordingly, TA's 4 and 6 and group 1A in TA 1 will not provide durability problems. The group of bars with less than 20 mm cover in TA 1 remains a potential problem area, and protective measures need to be taken. Additional cover depth measurements, however, suggested that the occurrence of such a low cover group of rebars in the center wall was an incident.

*5.2 **RCM analysis***

The RCM tests for validation were performed on concrete that was between 1 and 3 years of age. These RCM values are to be validated against a 28 day RCM value that is stipulated for the project. In order to do so the time-dependence model for chloride diffusion from DuraCrete [DuraCrete, 2000] is proposed:

$$D(t) = D_0 \left(\frac{t_0}{t} \right)^n \tag{1}$$

wherein $D(t)$ is RCM at time t, D_0 is RCM at 28 days, t_0 is 28 days, t is the age of the concrete at sampling and n is an ageing coefficient ($0<n<1$). In short the used procedure is as follows. Starting from the measured RCM value $D(t)$ the 28 days value D_0 can be calculated taking into account the age of the concrete samples as well as an aging value. This n-value was determined in the past by various researchers along two different paths. One line of research uses measured chloride profiles to which Fick's second law of diffusion is fitted to obtain a diffusion coefficient. When a number of diffusion coefficients have been obtained for similar types of concrete but of different age, the ageing coefficient can be obtained from the slope of the diffusion coefficient against time. This way values for n have been found according to DuraCrete [DuraCrete, 2000] for blast furnace slag cement of 0.6 (splash zone) and 0.85 (atmospheric conditions). More recent research following the same approach reveals values of 0.45 for marine environment [Polder, 2005; De Rooij, 2005].

Another possibility is to use the actual RCM values from specimens of different age. Similar concrete stored under water for periods up to three years have produced an ageing coefficient of n=0.38 [Visser, 2006]. Testing samples from structures of different ages by RCM produced values of about n=0.23 for structures around 20 years of age. As TNO was involved in the testing of the trial mixes of B/K for the Green Heart Tunnel, RCM values of these specific mixtures have been gathered up to one year of age, stored under water. For these mixes an ageing coefficient was found of n=0.26.

Summarizing, based on n values from various sets of RCM results, both from field exposure and from trial mixture results for GHT concrete, the n coefficient to be used in the analysis using Eq. (1) should lie between 0.25 and 0.30.

In order to analyse the measured RCM data in this study, it is tentatively assumed that all mixes can be considered as one homogeneous group with regard to chloride diffusivity, in spite of the fact that the concrete of the eight TA's was produced over a three year period in two plants. On the other hand, it is known for example, that the variation of cement content does not seem to have a large influence on the RCM value [Schiessl, 2004].

As the RCM samples have not only been taken from different test areas but also from different depths, it is possible to make an "RCM-profile" to check whether or not samples can be regarded as one group. As, an example, data for TA 1 are shown in Fig. 3. It shows that the mean values for each depth vary, but differences are within the experimental scatter. It can therefore be concluded that the diffusivity of the cover is similar to that of the bulk of the concrete, which is an indication of good curing conditions for the outer concrete. These results are similar for other TA's, which in our view supports that in this case the tested samples are representative for the achieved durability of the concrete with regard to chloride diffusivity. This may not be a general rule, however, as poor curing will strongly affect the cover concrete but less so the bulk concrete!

The measured RCM values are plotted as a function of concrete age at sampling in Fig. 4. The best fit through the measured data is obtained with an exponent of n = 0.27. This

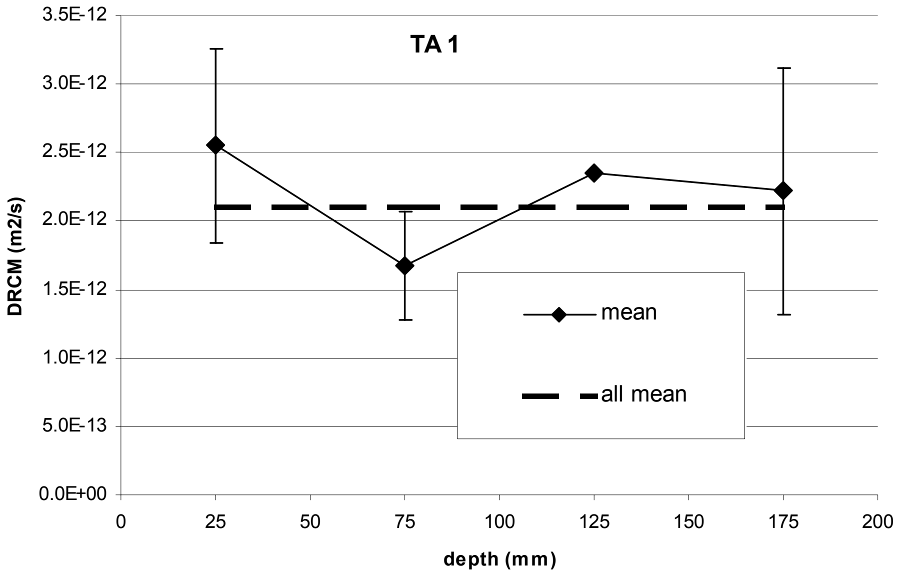

Figure 3: Variation of RCM values as a function of depth in TA 1; mean for each individual depth (solid symbols) and standard deviation indicated by error bars; mean of data for all depths in TA 1 (hatched line); number of samples per depth range: three from 0-50 mm; five from 50-100 mm; one from 100-150 mm; six from 150-200 mm.

results in a 28-day value of $D_0 = 3.5 * 10^{-12}$ m²/s. In Fig. 4 also the exponential decay lines have been plotted, starting at $D_0 = 5.0 * 10^{-12}$ m²/s using values of 0.25 and 0.30. It can be seen that the best-fitting line through the measured RCM values is located below these exponential decay lines. There is considerable scatter, but this is normal for RCM tests; a coefficient of variation (COV) for repeatability was found of 15% to 25% from extensive testing in 15 laboratories [ChlorTest, 2005]. Furthermore, the analysis supports that all data form one group and also supports the reasoning with regard to the aging exponent. Hence, the in-situ cast concrete meets the 28-day requirement of a maximum value of

$D_0 = 5.0 * 10^{-12}$ m^2/s and it has been possible to validate this at later ages. We realise, however, that the understanding of long-term aspects of chloride diffusivity in concrete is far from complete. For recent views on long term diffusivity modelling, see [Lay, 2003; Visser, 2006].

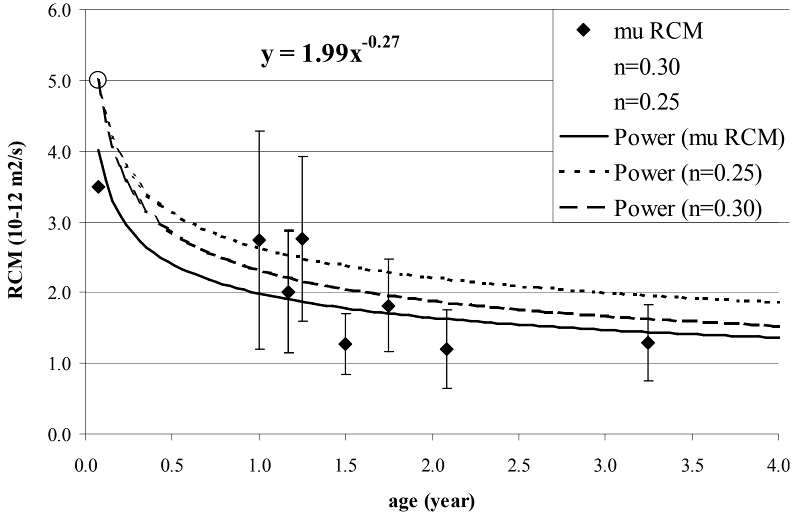

Figure 4: RCM results: mean values of 12 samples per test area (solid symbols), standard deviations indicated by vertical error bars. Solid line is best-fit. Large white circle top left is specified maximum value at 28 days; black diamond underneath white circle is extrapolated (to 28-days value) of best-fit line.

5.3 ***TEM analysis***

Could the good validation results have been foreseen based on the TEM measurements during production? To answer this question Table 5 is used. As can be seen in Table 5, standard deviations for TEM results are rather small relative to mean values; COV's ranged from 0.02 to 0.06. Multi-laboratory research also showed low COV's for resistivity testing [ChlorTest, 2005]. In our case the low COV's suggest that the variability within each day production was small. For such a low COV, the required minimum resistivity was specified to be 260 Ωm. The batch mean resistivity was higher than this requirement in all cases, with a lowest value of 275 Ωm at 28 days (Table 5). Consequently, according to the quality control testing, all batches related to our TA's complied with the TEM requirement. As the RCM's from these TA's also complied with the service life design requirement (see

Section 5.2), it was concluded that the quality control testing was adequate, both with regard to the procedure followed and with regard to the achieved durability of the concrete.

6 Conclusions

For cast in situ concrete parts of a large train tunnel, cover depths were measured and concrete was sampled for testing in order to assess compliance with the design for a service life of 100 years and to validate the quality control during production with regard to durability. The service life requirements were based on possible (future) exposure to chloride ions and carbonation. Eight test areas were chosen to include a variety of structural parts and technological/environmental conditions. The concrete in these test areas was produced using blast furnace slag cement over a period of three years in two mixing plants.

Cover depths at five out of eight test areas complied to the requirement (except a single incident). For the other three test areas, it was shown that chloride exposure was highly improbable due to the position of those parts. In those cases, cover depths were sufficient to exclude carbonation induced corrosion, with the exception of one group of bars at very low cover depth, which needs additional protection. Additional cover depth testing showed that this group was an incident.

Cores taken from the test areas were tested for chloride diffusivity using the Rapid Chloride Migration method. The age of the concrete when sampled ranged from one to three years. It was found that the chloride diffusivity did not significantly vary with depth from the surface down to 200 mm. This suggests that the curing of the concrete had been adequate. Diffusion coefficients were calculated back to 28-day values using an empirical model, taking into account the decrease of diffusion coefficient through time due to hydration. The results showed that the concrete had a consistently low chloride diffusivity and complied with the requirement.

During production, quality control was carried out by non-destructive electrical resistivity testing of cubes (intended for strength testing) at 28 days age. Acceptance of the results was based on statistical analysis of the correlation between resistivity and diffusivity and on the variation present in each batch. According to the procedure, all batches of concrete used to produce the concrete in the test areas complied with the criterion. As testing of samples from those test areas showed satisfactory chloride diffusivity, it is concluded that quality control by resistivity testing as carried out in this project was successful.

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