Long term behaviour of the resistivity of concrete

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Against the background of immense costs of repair or replacement of concrete structures degraded by reinforcement corrosion, a strong interest in industry and research can nowadays be found in the underlying processes and in possibilities to influence them. As a part of the reinforcement corrosion circuit, the resistivity of concrete is a decisive material parameter with regard to corrosion propagation, which itself is a time-dependent process of many years of length. For this reason, a picture of the long term behaviour of the resistivity of concrete could be of great value.

This paper presents resistivity data of concrete specimens up to an age of 17 year. An investigation was carried out of their development throughout the years in dependence of all main aspects influencing the magnitude and the development of the resistivity (climate, cement type, water/cement-ratio).

Key words: Concrete resistivity , ageing, moisture, cement type, blast furnace slag cement

1   Introduction

Ordinary (carbon) steel reinforcement in concrete is protected from corrosion by the alkalinity of the surrounding concrete, which leads to the formation of a passive layer on the steel surface. The loss of alkalinity caused by carbonation and the ingress of chlorides may destroy this protection of the reinforcement steel. In case of chlorides penetrating into the concrete and reaching the steel surface, a spatially limited (local) loss of the passive

layer takes place and depassivated areas become the anodes of corrosion elements. Because of the electric potential difference with the anode the adjacent steel surfaces work as cathodes as they are still passivated, further supporting a pitting type of attack. Generally, for carbonation induced corrosion, bigger anodic areas are found in concrete, caused by a relatively steady propagation of the carbonation front in the concrete. Here, the steel depassivates uniformly and a more or less uniform steel degradation takes place. Both types of corrosion initiation result in the same overall corrosion reactions. Iron ions (Fe^{2+}) dissolve from the steel surface at the anode whose negatively charged electrons ($2e^-$) are transported through the steel to the cathode. There, these electrons react with water and oxygen and form negatively charged hydroxyl ions (OH^-). Via the pore liquid, the negative charge is transported from cathode to anode where they form corrosion products e.g. hydrated Fe_2O_3 (rust); positive charge will be transported in the other direction although at a lower level due to lower mobility of sodium and potassium ions. The larger the distance between anode and cathode, the larger is the influence of the electrolytic (ionic) conductivity, or its inverse the resistivity, of the concrete in between. The resistivity of concrete is a material-specific and geometrically independent parameter describing the ability of the concrete to allow or constrain charge transport processes. More generally, resistivity reflects the ease of ion transport in concrete, including chloride penetration; the relationship between inverse resistivity and chloride diffusion can be used as basis for a quick method for estimating chloride penetration resistance in service life design, see [Wegen, van der, et al., this issue]. In addition, chloride transport is needed for corrosion pits to grow from the early stages of nucleation and developing into sustained pitting [Page & Havdahl 1985, Lambert et al. 1991, Glass et al. 1991, Polder 2009, Angst et al. 2011] Specifically, a higher resistivity of the concrete is accompanied by a slower corrosion propagation of the reinforcement steel [Alonso et al. 1988, Glass et al. 1991, Fiore et al. 1996, Bertolini & Polder 1997, Angst et al. 2011]. Consequently, it is important to know the magnitude of the resistivity and its influencing parameters. The resistivity, is defined as the inverse of the conductivity, Equation 1,

$$\rho_e = k_e \frac{U_x}{I_x} = \frac{1}{\sigma} \tag{1}$$

where ρ_e is the electrolytic resistivity of concrete in [Ωm], k_e is a geometrical "cell" constant, which for two flat electrodes on either side of a rectangular specimen can be obtained by dividing the conducting concrete cross-section [m²] by the distance between the electrodes in [m], $\underline{U}_x$ is the potential difference between the electrodes in [V], I_x is the current flowing

between the electrodes in [A] and σ is the conductivity in $[\Omega^{-1}\cdot m^{-1}]$. For non-planar electrodes, e.g. bars embedded in a specimen, a similar cell constant can be defined.

Due to early research [Berke 1989, Berke et al. 1992, Bürchler et al. 1996, Cabrera and Ghodoussi 1994, Catharin and Federspiel 1972, Elkey and Sellevold 1995, Whittington et al. 1981] into concrete resistivity, a better understanding has emerged of the mechanisms concerning ion and current transport in concrete. Many studies have figured out that the moisture content is the main parameter influencing the resistivity [Fiore et. al. 1996, Gjørv and Vennesland 1977, Hope and Ip 1985, Osterminski et al.(1) 2006, Raupach 1992, Tritthart and Geymayer 1985, Yamamoto and Masuda 2003]. Dried out concrete behaves like a (semi-)insulator permitting practically no movement of ions or charges, whereas an increase in water content in the pore system of the concrete significantly decreases its resistivity. Charges can more quickly be transported from cathode to anode due to the higher conductance of a larger volume of pore liquid. The temperature as another environmental parameter also influences the resistivity. As for most chemical processes, the temperature dependence of charge transport from cathode to anode can be expressed by the theoretical approach of Arrhenius [Raupach 1992, Schießl and Raupach 1994, Bürchler et al., 1996]. Thus, an increase in temperature is accompanied by an increase in the mobility of the dissolved ions in the pore liquid and consequently its conductivity.

Regarding the influence of the concrete composition, each material parameter changing the porosity, the pore liquid composition and the pore structure of the concrete also influences the resistivity, as a continuous pore structure between anode and cathode is needed to transport charges. Thereby, the most significant effect can be observed by varying the type of binder [Berke 1989, Berke et al. 1992, Gehlen 2001, Osterminski et al.(1) 2006, Polder et al. 1991, Polder and Peelen 2002, Roper et. al. 1994]. Cements containing latent hydraulic or pozzolanic materials like blast furnace slag or fly ash can achieve resistivities being up to 3 to 4 times higher than those of ordinary Portland cement [Polder and Peelen 2002, Osterminski et al. 2006(2), Ortega et al. 2013] – under the same conditions of moisture and temperature. For cements blended with latent-hydraulic or pozzolanic materials, the time-dependent development of the resistivity has to be taken into account. The hydration of slag and fly ash, which densifies the pore structure and increases the resistivity, is slower than that of Portland cement clinker. However, slag reacts relatively fast (depending on its type and fineness), on the time scale of weeks, see

a.o. [Caballero et al., 2012, this issue], while fly ash reacts much more slowly, i.e. over months [Polder 1996, Polder & Peelen 2002, Valcke et al. 2012, this issue]. Another factor influencing the porosity of concrete is the water/cement-ratio. Higher w/c-ratios form a coarser pore structure which allows a stronger and faster ingress and evaporation of water into or out of concrete. At constant moisture state an increase in w/c-ratio leads to a decrease in resistivity [Fiore et al. 1996, Osterminski et al. 2006(1), Raupach 1992, Ortega et al. 2013].

The aim of this paper is to report long-term data for the time-dependent behaviour of the resistivity of concrete made with Portland and Blast Furnace slag cement and to investigate the main influencing factors.

2 Resistivity experiments

2.1 Specimens and materials

In 1989, a set of concrete specimens has been cast in order to investigate the effect of cement type, water-to-cement ratio and external humidity on the resistivity of concrete. Therefore, 30 cubes (150 mm) with four pairs of embedded brass electrodes with a diameter of 6 mm at a center-to-center distance of 50 mm parallel to the casting direction were made. Slightly modifying the arrangement used by [Tritthart and Geymayer 1985], each pair of electrodes was embedded vertically at different depths (10 mm, 15 mm, 20 mm and 50 mm) such that a study of moisture changes at four depths was possible (Figure 1). As the brass bars were exposed (not insulated) over their complete length of 150 mm, there may be an effect of their outer parts being at a smaller distance to the outer surface than their nominal distance. It is believed that the effect is small, however. Cell constants (k_e, Equation 1) were determined from resistance measurements using electrodes in an identical arrangement placed in solutions of known conductivity. They had typical values of about 0.1 m.

The concrete compositions used for casting the specimens can be seen in Table 1. Two different cement types were used; ordinary Portland cement corresponding to a modern CEM I 32.5 R and blast furnace slag cement with 70 % of slag content, which corresponds to a modern CEM III/B 42.5 LH HS. For both cements, mixes were made with three water-to-cement ratios (w/c), 0.45, 0.55 and 0.65. The cement content was kept in a small range (320-326 kg/m³) and can be considered as nearly constant. Some variation of cement paste volume occurs. Nevertheless, the porosity of the cement paste strongly depends on the variation of w/c. This may overemphasise the effect of w/c on resistivity to a certain

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degree. The aggregates were (rounded) siliceous river sand and gravel with a maximum size of 16 mm. After casting and demoulding at one day age, cubes were stored in a fog room at 20°C until 28 days age. Sets of six cubes (one cube for each composition) were then distributed between various climate rooms: 20°C 50% RH; 20°C 65% RH; 20°C 80% RH; 20°C 90% RH (these were transferred to a fog room at >95% RH and 20°C at age 200 days). One set was stored in two plastic containers filled with tap water in the laboratory at 20°C, one container for CEM III/B specimens and one for CEM I specimens. The containers with
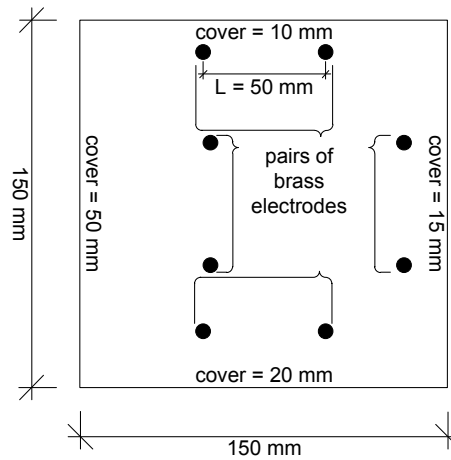

Figure 1: Electrode setup of two brass electrodes for each of the four cover depths in a cube specimen

Table 1: Concrete compositions for resistivity specimens

	CEM I			CEM III/B		
w/c-ratio (-)	0.45	0.55	0.65	0.45	0.55	0.65
Aggregate (kg/m³)	1,900	1,857	1,789	1,897	1,853	1,790
Cement content (kg/m³)	325	326	320	325	325	320
Water content (kg/m³)	146	179	208	146	179	208
Wet density (kg/m³)	2,371	2,362	2,317	2,368	2,357	2,318

these specimens were transferred to outside/unsheltered exposure at an age of about 7.5 years. From this moment on, the water level in the containers was not checked carefully; in some periods the level may have been low and the cubes may have dried out slightly. At about 4800 days, the last measurements were taken on the specimens in the original exposure conditions. Related to moving the laboratory from Rijswijk to Delft in 2003/2004 (at about 5000 days age), specimens were stored inside for several months and some specimens were lost. Finally, since mid 2004, the remaining specimens are exposed unsheltered on the roof of the TNO laboratory at Delft, The Netherlands. These are three cubes of each cement type and w/c-ratio which were previously stored in three different climates (submerged/outside; fog room; 80% RH). Figure 2 shows the history of the specimens in terms of their storage conditions.
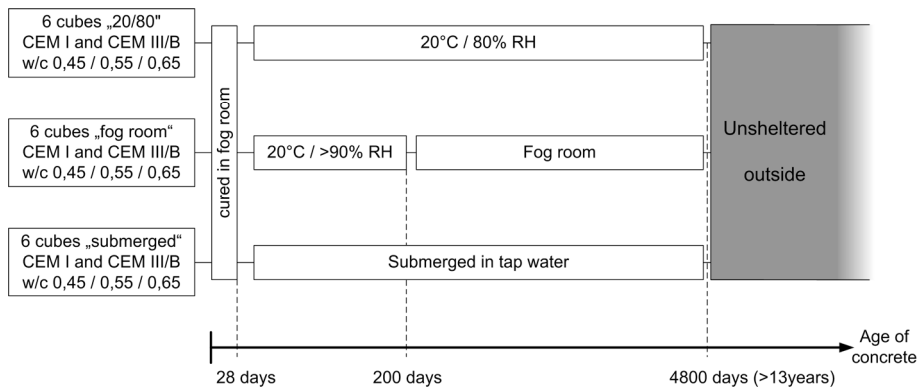

Figure 2: Overview of curing and storage of specimens

2.2 *Measuring instruments*

As part of a bigger research programme, a resistance measuring instrument combined with a data-logging system (termed cbm data logger) was developed [Osterminski et al. (1) 2006]. It applies an alternating sinusoidal current (I) at 107 Hz and measures the resulting potential difference (*U*) between the electrodes (here: the two brass bars). The measured resistance was multiplied by the cell constants which are of the order of 0.1 m [Polder and Ketelaars 1991] to estimate the resistivity of the concrete (Equation 1). In 1989 and 1990 a high precision AC bridge was used to determine the resistance of the concrete with a measuring frequency of 1 kHz; from 1991 another bridge with 108 Hz frequency was used. A portable resistance meter, type ESCORT LCR using AC at 120 Hz, was used since the mid 1990's and was employed in 2006 to verify the values from the cbm data logger. For

assuring the comparability of both measuring devices, calibration measurements on 26 specimens were carried out before the actual measurements. These results showed good agreement as shown in Figure 3. The measurements after 1993 (around 1700 days) were taken irregularly. The last measurement was taken in 2006 (at an age of about 6200 days), using the cbm instrument.
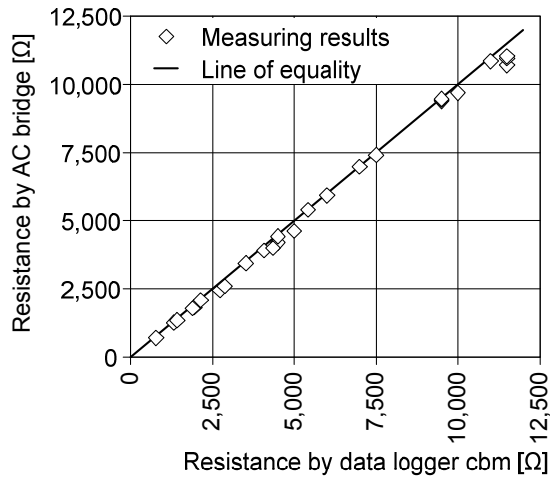

Figure 3: Resistance obtained using the portable AC resistance meter (120 Hz) and the data logger developed at the centre for building materials (cbm) at TU München (107 Hz).

3   Results and discussions

3.1   *Resistivity and depth of electrodes*

Previous results were reported in [Polder and Ketelaars 1991]. Summarising: at age 28 days, Portland cement concrete delivered resistivity values which were three times lower than those of slag cement concrete. Coefficients of variation for six specimens of the same composition (measured with four electrode pairs) were about 5 to 10%. Over the subsequent years, resistivities increased with time. At 670 days, values varied widely, depending on cement type, external humidity and the depth of the electrodes. For submerged specimens, Portland cement concrete had lower values than slag cement concrete of the same w/c-ratios. These values were considerably higher in semi-dry climate (80% RH) for each cement type, with yet higher values for electrodes near the surface and lower values at 50 mm depth. For a more detailed picture of resistivity as a

function of composition, depth and climate at 670 days, see Annex A. In addition to the values mentioned, drying out is clearly shown for cubes in 65% and 50% RH, with much higher resistivity values at 10 and 15 mm depth than at 50 mm depth. The difference is more than a factor two.

In April 2006, all cubes were measured on the same day at an age of 6,177 days (≈ 17 years). The temperature during measurements was approximately 10°C and the weather condition was dry – no wet surfaces of the cubes due to rain were observed. The complete data set can be found in Annex B and C.
The development of the resistivity of a CEM III/B specimen with w/c 0.45 for the four investigated cover depths can be found in Figure 4.
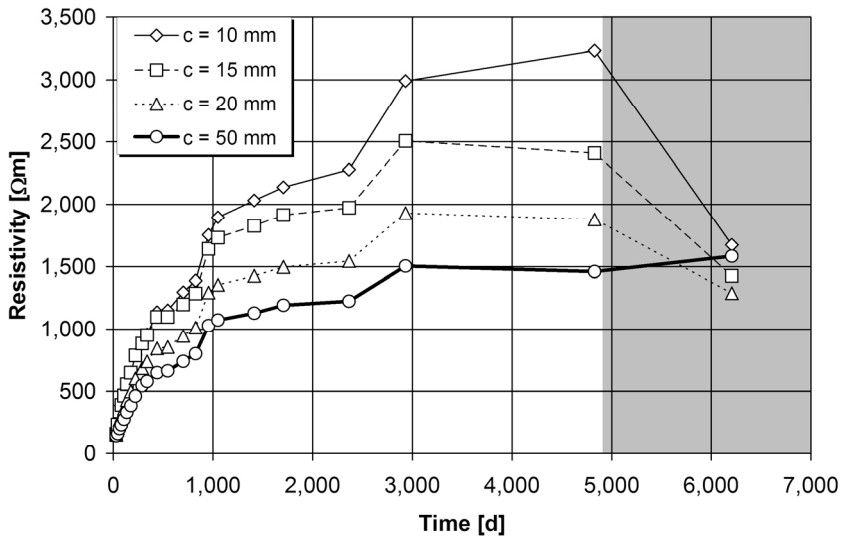

Figure 4: Resistivity of a CEM III/B specimen with w/c-ratio 0.45 at four different cover depths stored in 20°C and 80% RH (area with white background) until rearrangement outdoor unsheltered (grey background)

In the Figure, a rather steady increase of resistivity is shown until the moment at which the specimen was removed from its original climate (20°C/80% RH) via storage indoor to the present storage outdoor This increase, during the 20°C/80% RH storage was stronger for smaller cover depths (10 mm, 15 mm and 20 mm) due to stronger drying out in the outer zones of the concrete. A relative dip can be noted in this Figure (and others) around 2300

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days. The cause is unknown, but it may have to do with high temperatures, as this point corresponds to August 1995. By rearranging the specimen to outside exposure after 4,800 days (≈ 13 years) of concrete age, a drop of the resistivity for smaller cover depths could be observed. The outer zones of the concrete may have been wetted by rain events a few days before, although, on the day of measuring, no sign of water was found on the concrete surface. The resistivity at 50 mm cover depth, however, was still steadily increasing after the rearrangement. This shows that the resistivity of concrete at greater depths is less affected by short-term rain events and dry periods of moderate lengths (weeks to months). The steadily increasing trend in the 50 mm results from indoor at 80% RH (up to 4,800 days) to outdoor (at 6200 days) shows that at such a depth CEM III/B concrete exposed outside without shelter still approaches equilibrium with 80% RH. However, at shallower depths (10 to 20 mm), drying out in 80% RH causes increased resistivity, and subsequent exposure to rain decreases resistivity.

In Figure 5 the time dependent behaviour of the resistivity of a CEM I specimen with w/c 0.45 at four depths is shown. Considering that this specimen was stored in the same climate as the one whose results are shown in Figure 4, the CEM I specimen's resistivity values were three to four times lower than those of the CEM III/B specimen after 4,800 days (≈ 13 years). After the rearrangement, the values at shallower depths did not show an
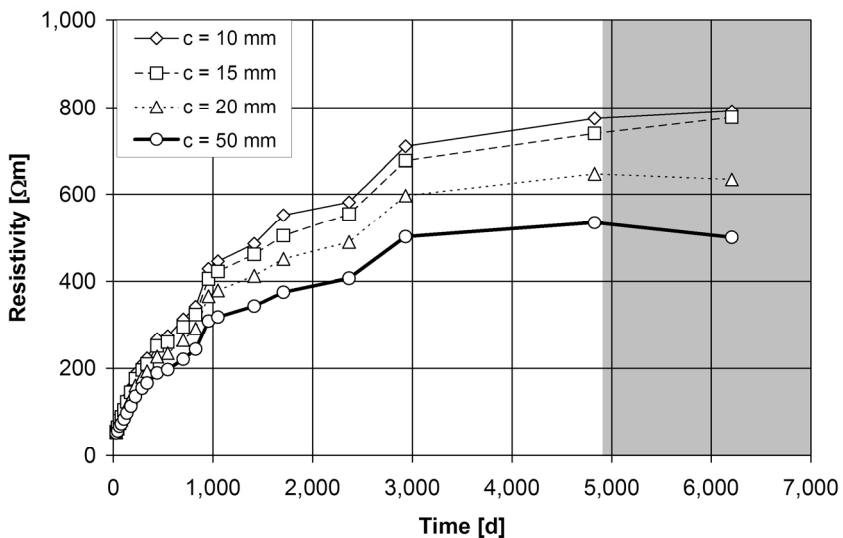

Figure 5: Resistivity of a CEM I specimen with w/c-ratio 0.45 at four different cover depths stored in 20°C and 80% RH until rearrangement outside/unsheltered (grey-highlighted)

unsteady development as obtained for the CEM III/B specimens. Using the results from the electrodes at 50 mm depth, measurements should therefore provide good information about the time development of resistivity of concrete made with both CEM I and CEM III/B.

Originally, sets of specimens were also exposed in 20°C 50% RH and 20°C 65% RH, which are no longer available. For reference, their results at 4,800 days age are presented in Annex B. Summarising these results, all outer layers had much higher resistivities than the inner layers; all w/c 0.65 specimens had higher values than w/c 0.45 specimens, with w/c 0.55 in between; and CEM III/B concrete had higher values than CEM I concrete.

3.2 *Time-development of resistivity*

Figures 6 through 8 show the results of the resistivity measured at 50 mm depth for all specimens . Results for each w/c-ratio are plotted in one diagram in dependence of time, cement type and original climate. The values represent the resistivities measured using the 50 mm electrodes only.

Figure 6: Resistivity of concretes with w/c-ratio 0.45 at 50 mm cover depth stored in three different climates until rearrangement outside/unsheltered (grey-highlighted)

Figure 7: Resistivity of concretes with w/c-ratio 0.55 at 50 mm cover depth stored in three different climates until rearrangement outside/unsheltered (grey-highlighted)
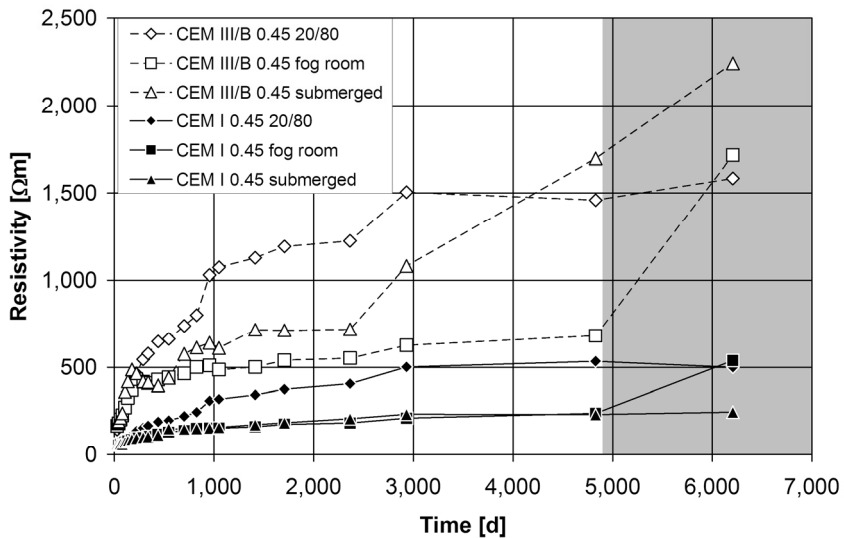

Figure 8: Resistivity of concretes with w/c-ratio 0.65 at 50 mm cover depth stored in three different climates until rearrangement outside/unsheltered (grey-highlighted)
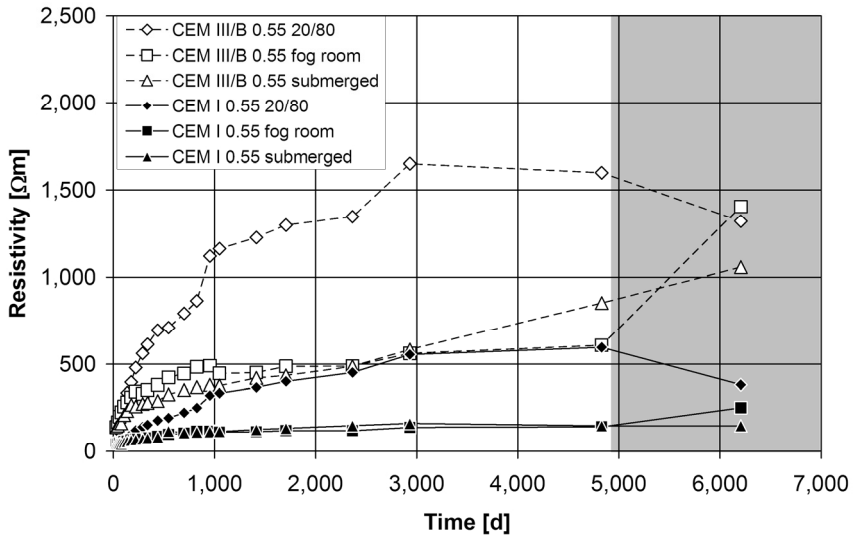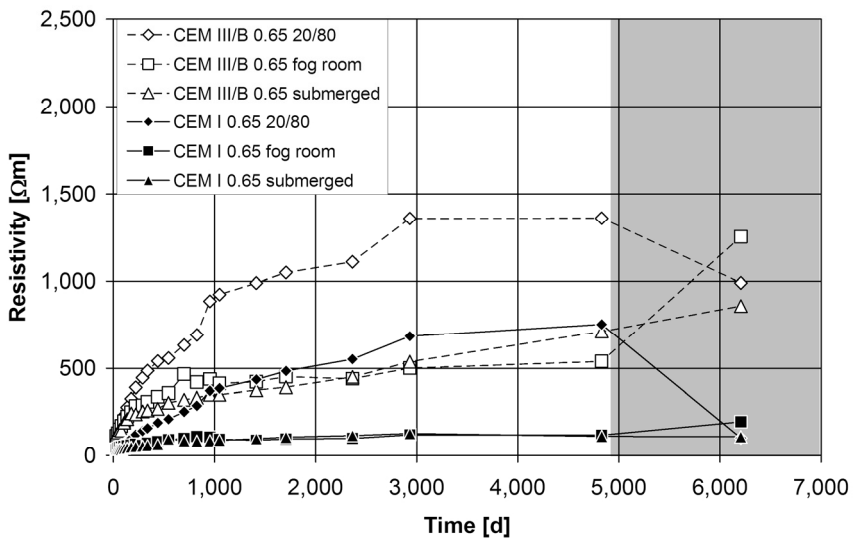
The highest resistivities before the rearrangement were obtained for the CEM III/B specimens as expected. Here, on-going hydration of the slag caused densification of the pore structure as well as the reduction of the ion concentration in the pore liquid which is needed for the charge transport through the concrete. Thus, a strong influence of the type of binder on the time dependent behaviour of resistivity can be found.

The CEM I specimens stored in moist climates reached an ultimate resistivity value at approximately 1,000 days ($\approx$ 3 years), whereas the development of the CEM III/B cement concretes continued. Hereby, the hydration process of the slag seemed to take an important part in the resistivity development, especially for the submerged specimens. It is likely that unhydrated particles in the cement matrix formed new CSH-phases by consuming OH^- and densifying the pore structure. This effect was stronger for lower w/c-ratios, due to a higher amount of unhydrated materials in the cement matrix. In combination with a constant water supply, on-going hydration increased the resistivity of concrete. An increase of the resistivity due to leaching of ions in the pore solution can be excluded for the following reasons:

- The original concentration of ions is higher in pore solutions of CEM I compared to CEM III/B concretes, leading to a higher expected level of leaching in CEM I concretes. This should be accompanied by an higher increase in resistivity, which is not found in the present results.
- The leaching of ions is higher at higher capillary porosity, which is influenced by the w/c-ratio. The slope of the resistivity over time should therefore be steeper for higher w/c-ratios. This cannot be found here.

Presuming that the hydration process of the CEM I specimens ended after approximately 1,000 days, the further increase in resistivity of the 20°C 80% RH specimens can be explained by drying out in this climate; and possibly carbonation (see below).

A proof for the dry-out behaviour of the CEM I specimens is the resistivity at 4,800 days which was higher for higher w/c-ratios. The resistivity value for the 20°C 80% RH climate of the w/c-ratio 0.55 specimen after 4,800 days equalled the resistivity of the moist CEM III/B. For w/c-ratio 0.65 the resistivity of the CEM I specimen was even higher than the resistivity of both CEM III/B specimens stored in the fog room and submerged. This demonstrates the significance of the moisture content for the resistivity and the effect of a higher capillary porosity regarding drying out of concrete.

Sensitivity towards changes in their exposure climates can also be found for the specimens made with CEM III/B after their rearrangement. The resistivity of all specimens with a w/c-ratio of 0.45 increased. Hereby, the specimens originally stored in wetter climates increased strongly (the time span is too long to call it "suddenly"), whereas the specimen stored in 20°C 80% RH increased more steadily. This may be due to the water loss of these specimens during outside exposure, which is more intense for the wetter specimens. Additionally, the selected climate of 20°C 80% RH represents approximately storage outside under shelter in the Netherlands [Polder et al. 1991]. Therefore, the rearrangement of the CEM III/B specimens with w/c 0.45 at an age of 4,800 days to outside exposure without shelter did not mean a dramatic change of climate, leaving the hydration process at 50 mm depth more or less unaffected. For higher w/c-ratios (w/c 0.55 and w/c 0.65), an influence of the coarser pore structure and a higher moisture content due to direct rain can be found, as the resistivity value decreased for the specimens that was previously exposed to 20°C 80% RH.

The same behaviour was observed for the CEM I specimens. Here, a stronger influence of rain during the last 4 years leads to a stronger decrease for the CEM I specimens with w/c 0.55 and w/c 0.65. With respect to the resistivity values and the trend in time of the CEM III/B specimens under the same exposure conditions, the coarser pore structure of CEM I concretes may be an explanation for this.

Another parameter influencing the resistivity could be the carbonation of concrete throughout the years. The magnitude of this effect depends on the exposure of the specimen and also on the type of cement and w/c-ratio. For the examined cement types different effects can generally be expected. Carbonation increases the porosity of slag cement concrete [Copuroglu et al. 2006] due to an initially lower calcium hydroxide content, resulting in less calcium carbonate produced. Thus, the influence of wetting and drying would be more distinct than in Portland cement concrete. For the specimens reported here only a slight impact of such a carbonation effect on resistivity could have happened. Effects of hydration related to concrete composition, in particular cement type, seem to be more significant than carbonation. However, without carbonation depth measurements this effect cannot be precisely assessed.

In general, the results of this paper agree with investigations of resistivity of old concrete found in the literature [Polder and Larbi 1995, Polder and de Rooij 2005].

4 Conclusions

As the results of the resistivity measurements represent only one value for each cover depth, specimen and original climate, a statistical analysis cannot be given. Nonetheless, the resistivity behaviour proved the expected tendencies known from the literature and can be judged as a valid long-term view into time-dependent resistivity development of concrete. Against this background, the following conclusions can be drawn.

1. Weather changes influenced the resistivity, depending on the capability of the concrete to absorb water during rain events and release it during dry periods. In this regard the cement type and the w/c-ratio were the most significant influencing parameters. A decreasing w/c-ratio resulted in a decrease in sensitivity for moisture fluctuations, whereas this sensitivity was more distinct for CEM III/B cement concrete than for CEM I cement concrete.

2. The beneficial effect of slag cement (CEM III/B) for an increased resistivity of concrete was confirmed. Over 17 years of exposure, measurements have shown a continued increase of resistivity, which confirms that the hydration of slag particles in the cement continues for a very long time. On the other hand, the hydration of the CEM I specimens (w/c-ratios 0.55 and 0.65) seemed to almost stop after approximately 3 years, showing no further significant change in resistivity due to hydration.

3. A w/c-ratio of 0.45 produced a steady development of the resistivity for both cement types.

4. The exposure to wetting and drying over about four years' time related to natural occurrence of precipitation (with its inherent temporal variation) after the previous exposure of the specimens for 13 years in a constant laboratory climate did not have a strong impact on the results of the resistivity at a cover depth of 50 mm. In other words, a medium depths in concrete, the previous history of exposure does not have a strong influence on the resistivity on the long term in a given environment.

In subproject A3 of the DFG research unit 537 "modelling of reinforcement corrosion" [Schießl and Osterminski 2006], the resistivity of concrete will be modelled as a part of the description of a macro cell corrosion element. In the model, a factorial approach will be used to describe the behaviour of the resistivity. The needed input parameters are obtained from numerous measuring results which could be statistically quantified. As a result, resistivity can be modelled as a scattering value. Modelling the development of resistivity over time- may be based on modelling cement hydration. Such a hydration based model can be validated with the long term data described in this paper [Osterminski 2013].

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Annex A. Additional results of resistivity measurement of CEM I 32.5R and
CEM III/B 42.5N LH HS concrete specimens at an age of 670 days (values in Ωm) at 20°C

Cement-type	w/c-ratio	Exposure	Concrete cover to electrodes			
			10 mm	15 mm	20 mm	50 mm
CEM III/B	0.45	50% RH	3,841	3,208	2,597	1,756
	0.55		3,730	3,241	2,445	1,426
	0.65		3,785	4,451	2,597	1,137
	0.45	65% RH	2,430	2,588	2,457	1,282
	0.55		1,998	1,619	1,439	1,071
	0.65		1,965	1,676	1,334	841
	0.45	80% RH	1,296	1,197	944	739
	0.55		1,254	1,177	907	792
	0.65		1,188	1,048	852	634
	0.45	Fog room	478	490	431	465
	0.55		467	507	446	396
	0.65		428	418	401	466
	0.45	Submerged	436	425	507	576
	0.55		365	357	351	351
	0.65		347	335	319	321
CEM I	0.45	50% RH	1,235	1,121	917	554
	0.55		1,798	1,565	1,217	701
	0.65		3,326	1,915	1,615	788
	0.45	65% RH	573	531	484	356
	0.55		633	608	502	364
	0.65		1,041	693	480	383
	0.45	80% RH	313	295	264	220
	0.55		312	295	264	223
	0.65		445	391	351	252
	0.45	Fog room	148	144	144	139
	0.55		109	108	107	106
	0.65		113	102	99	099
	0.45	Submerged	153	154	149	148
	0.55		114	110	105	108
	0.65		85	84	80	86

Annex B: Additional results of resistivity measurement of CEM I 32.5 R and CEM III/B 42.5 N LH HS concrete specimens at an age of 4800 days (values in Ωm)

Cement-type	w/c-ratio	exposure	concrete cover to electrodes			
			10 mm	15 mm	20 mm	50 mm
CEM III/B	0.45	50% RH	67,388	24,864	11,700	7,620
	0.55		303,363	267,177	29,566	7,153
	0.65		358,641	417,582	292,851	8,118
	0.45	65% RH	18,803	9,288	8,203	4,257
	0.55		57,942	18,992	6,233	3,860
	0.65		98,513	74,370	38,920	3,842
	0.45	80% RH	3,234	2,410	1,879	1,460
	0.55		X	X	2,036	1,599
	0.65		9,920	7,542	2,747	1,361
	0.45	Fog room	828	753	716	681
	0.55		669	682	608	534
	0.65		620	606	562	539
	0.45	Submerged	1,128	1,399	1,179	1,697
	0.55		956	958	932	852
	0.65		830	787	691	712
CEM I	0.45	50% RH	10,079	9,595	8,157	9,240
	0.55		49,950	31,968	30,420	8,911
	0.65		X	296,400	71,370	10,864
	0.45	65% RH	3,120	2,734	2,489	1,909
	0.55		4,897	4,684	3,539	2,601
	0.65		70,308	16,108	29,559	3,003
	0.45	80% RH	774	740	647	534
	0.55		852	835	685	596
	0.65		3,440	1,935	1,202	753
	0.45	Fog room	264	270	253	237
	0.55		149	154	146	142
	0.65		118	129	118	118
	0.45	Submerged	272	239	254	231
	0.55		152	162	147	149
	0.65		123	119	119	111

X: not measured or: could not be measured (because out of instrument scale)

Annex C. Results of resistivity measurement of CEM I 32.5R and CEM III/B 42.5N LH HS concrete specimens at an age of 6206 days (values in Ωm) at approximately 10°C (outdoor exposure)

Cement-Type	w/c-ratio	Original Exposure	Concrete cover to electrodes			
			10 mm	15 mm	20 mm	50 mm
CEM III/B	0.45	80% RH	1,674	1,425	1,287	1,584
	0.55		1,832	1,832	1,170	1,320
	0.65		1,277	1,332	1,112	990
	0.45	Fog room	2,484	1,653	1,638	1,716
	0.55		1,620	1,596	1,404	1,716
	0.65		1,110	1,221	1,112	1,254
	0.45	Submerged	1,388	1,832	1,463	2,244
	0.55		1,188	1,197	1,170	1,056
	0.65		999	944	819	858
CEM I	0.45	80% RH	792	777	635	500
	0.55		230	247	199	383
	0.65		302	483	167	102
	0.45	Fog room	500	555	412	538
	0.55		216	319	252	251
	0.65		194	197	187	195
	0.45	Submerged	302	251	278	244
	0.55		147	167	146	149
	0.65		124	120	120	109