24 Years of experience with the electrical conductivity to determine material properties of concrete

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24 Years ago, the concept of using the electrical conductivity to characterize the strength development of young concrete was the starting point for a research program that resulted in the ConSensor. This sensor system is now used all over the world to monitor the strength development of young concrete. Scientists of several universities are now interested in other possibilities to use the electrical conductivity as a parameter to monitor concrete because it is not only related to the strength development it also gives information about other characteristics like the setting time and the durability of concrete.

In this paper the latest experience and research results will be presented, including the relationship between electrical conductivity and

- **strength;**
- **setting time;**
- **durability of concrete;**
- **conductivity and temperature.**

The first three topics find their origin in the microstructure of cement and how this microstructure changes in time. These relationships can therefore be described with microstructural models. The fourth topic, the temperature coefficient is based on the theory of the activity of ions in the pore water.

Keywords: Material model, electrical conductivity, strength development, material characterisation, microstructure

1 Introduction

There is a need for information about the behaviour of materials in structures. This information is required to monitor the construction process and to have figures about the quality of the materials used. For concrete the information about the hardening can be used to optimise the speed of construction. Information about the microstructure of the material like the permeability can be valuable to determine the durability. The information is preferably gained in a non-destructive manner. The ConSensor, a wireless sensor system that measures the electrical conductivity and temperature of (hardening) concrete, has been designed for this purpose. In this paper the applications and results over the past 24 years are discussed.

The idea behind the ConSensor started as a scientific concept based on the use of dielectric sensors to characterize microstructures [1]. The research that followed resulted in a concept that used the idea that the electrical conductivity of concrete changes in time due to the hydration of cement [2]. The changes in composition of the pore water in combination with the consumption of water and the changes in the connectivity of the pores results in changes in the electrical conductivity. These changes are mainly related to the hydration of cement. By combining material models and test data it is possible to relate the electrical conductivity to other material properties like strength. This scientific concept was later adopted for practical applications and is now commercially available.

2 Theoretical background

The electrical conductivity of concrete depends on many factors like the type of cement, temperature, pore structure, degree of hydration etc. It is therefore needed to understand the theoretical background of the electrical conductivity if this material property is used as an indicator for other properties.

The general idea of the electrical conductivity of hydrating concrete is that the electrical conductivity depends on a) the amount of free pore water and the quantity of ions therein and b) on the pore structure of the hardening concrete. As the degree of hydration increases the amount free water and ions decrease, and the number of connected pores decreases as well. Both factors cause the decrease of the electrical conductivity.
A simple model (figure 1) of conductive and not conductive resistors (R) has been used to show general idea of the relation between the degree of hydration of cement and the conductivity of the cement paste. It shows also the influence of the number of pores that are blocked. This principle was presented in the Heron journal in 1999 [22]. It was shown

that this model, in combination with a degree of hydration model and measurements of the conductivity, could be used as an indicator of the connectivity of the pores.

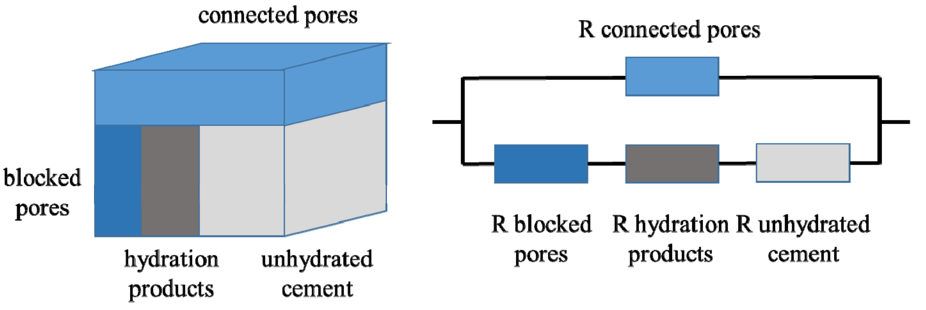

Figure 1: Electrical model of conductive elements based on the volumes on the volume fractions in the cement matrix

In this model the electrical conductivity of the pore water was taken constant during hydration to show the effect of blocked pores on the conductivity of the cement matrix. In reality the conductivity of the pore water will change in time. In the early stage the conductivity will increase because more ions will be present in the pore water due to the dissolving of the cement particles in the water. In the following phase the total amount and type of ions will be more stable resulting in a more constant conductivity of the pore water. External ingress of ions, for example caused by chloride ingress, can also cause changes in the conductivity of the pore water.

The main factors that determine the conductivity of concrete:

- Conductivity of the pore water;
- Amount of pore water
  (Amount of water in the concrete, in the cement paste and in the aggregates);
- Connectivity of the pores that are filled with water.

Models that calculate the conductivity based on these three main factors can be used to describe the microstructure of the cement matrix. An example of the application of these types of models is the characterisation of pore size distribution based on the measured conductivity [3]. Also, the relationship between electrical conductivity and strength can be described in this manner.

3 Electrical conductivity and strength development

As soon as the amount of pore water decreases due to the reaction between water and cement also the electrical conductivity decreases. Due to the same reaction the volume of the solid phase of reaction products will increase. This solid phase of un-hydrated and hydrated cement will give the cement matrix its stability and structure and, therefore, strength.

A relationship between electrical conductivity and strength can be found by combining models that describe the following 2 relationships:

- Pore structure and electrical conductivity
- Pore structure and strength

Backe [4] described the relationship between conductivity and porosity for the cement matrix with Archie's law. The relationship between porosity and strength was described with models of Powers, Balshin and Schiller. A more refined method was proposed by van Beek [2] by using the degree of hydration concept [5]. The outline of this model is presented in figure 2. Both methods showed that there is a relationship between the development of the microstructure and the electrical conductivity. The research also

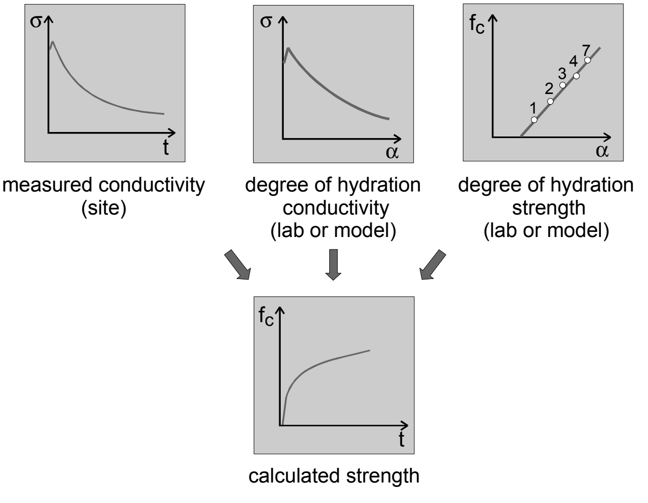

Figure 2: Outline of the model used describe the relationship between electrical conductivity and strength development [2]

showed that it is possible to make a direct relationship between the electrical conductivity and the strength.

The relationship between electrical conductivity and strength has been the basis for the first practical application of electrical conductivity on hardening concrete. It was the starting point of the development of the ConSensor. A system that, after 24 years of development, is being used all over the world.

The relationship between conductivity and strength as used for the ConSensor has shown to be reliable. The correlation coefficients of 54 mixtures have been examined. All mixtures showed the relationship. The average number for the correlation coefficient is 0,95. Each mixture, however, has its own specific correlation between electrical conductivity and strength as can be seen in figure 3. In this figure 4 concrete mixtures are presented. Each mixture varies in: type of cement, water – binder ratio, amount of aggregate, additives etc. These differences in the composition of the materials have an effect on both the electrical conductivity and the strength and thus on the conductivity strength relationship.

Many lessons were learned by using the ConSensor strength calculation in practice. The Consensor is used in numerous construction projects to determine when the formwork can

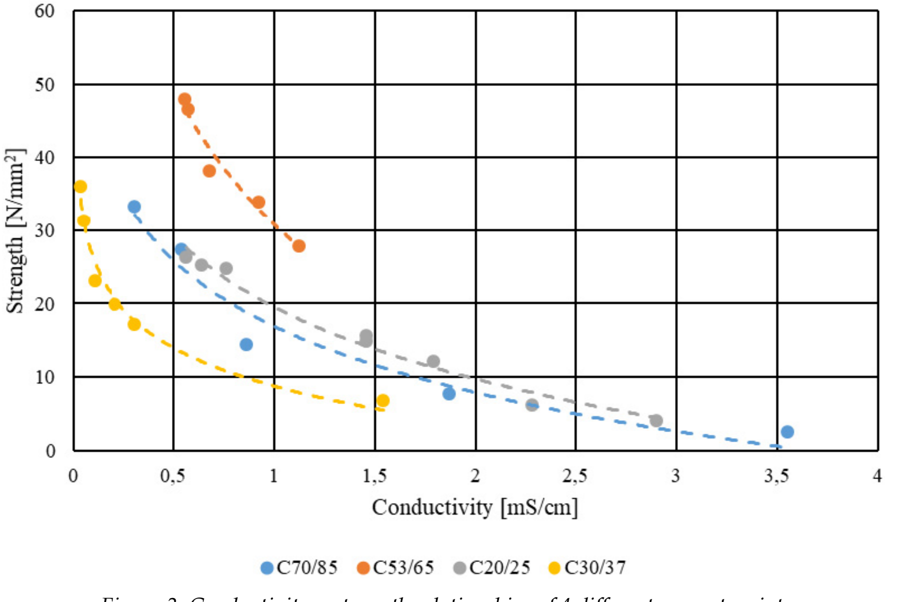

Figure 3: Conductivity – strength relationships of 4 different concrete mixtures

be removed and the prestress can be applied. In many cases the calculated strength from conductivity measurements has been compared to the calculated strength development based on the measured temperature (the weighted maturity concept). Both methods had the same reliability. One of the benefits of the conductivity method is that the starting point is clearly defined. The conductivity of young concrete is very high as long as the electrodes are in the air. There will be no electrical conductivity to be measured at all. As soon as the concrete is cast and contact between the electrodes and concrete is established, this is clearly visible in the measurements. These measurements are even used as an indicator to start the monitoring process of the strength development. Reinforcement can have an effect on the electrical conductivity. This can be dealt with by using relative measurements. This means that the maximum conductivity is used as a reference. On site the measurement system has to be simple and robust. A one button system has been designed with a simple user-friendly web-based interface. These lessons learned, and the feedback of the customers has resulted in several design modifications. To show this development over 24 years the first and latest versions are presented in figure 4.

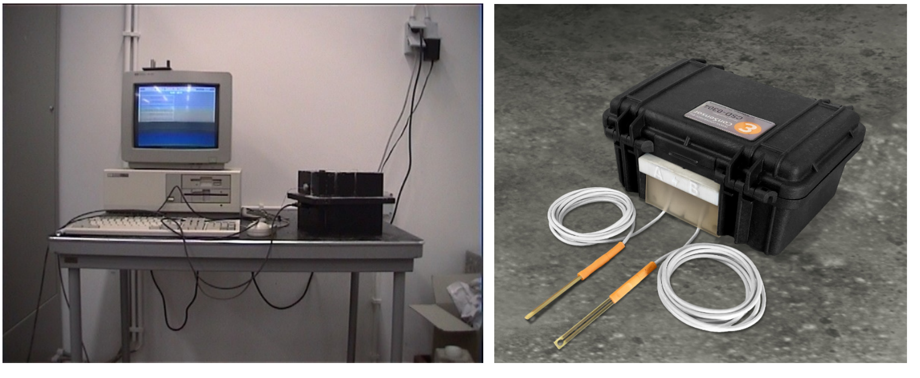

Figure 4: First design (left) and latest design (right) of the ConSensor

4 Electrical conductivity and durability

*4.1 **Chloride diffusion***

The electrical conductivity has a strong relationship with the pore structure in concrete. The pores that are connected and that are filled with water will conduct electricity from one electrode to another. This idea has been used already for testing the durability in the Duracrete concept [6]. It was found that there is a relationship between the electrical resistivity and the diffusion coefficient of concrete. The relationship between conductivity and diffusion coefficient was also observed by Kurumisawa [7] and described with the following formula:

$$y = 9.21 \cdot 10^{-11} x - 4.06 \cdot 10^{-12} \tag{1}$$

In which:

x	Conductivity (S/m)
y	Apparent diffusion coefficient (m^2/s)

To validate the idea of the relationship between conductivity and the diffusion coefficient the following investigation was done. The diffusion coefficient (D_{RCM}) was determined in 2 ways. Firstly, the D_{RCM} was determined based on the relationship between the electrical resistivity (TEM) and D_{RCM}. Secondly, the D_{RCM} was obtained from the empirical based relationship between water cement ratio and the D_{RCM} in which the cement type used was taken into account. The formula for the relationship between TEM measurements and the Diffusion coefficient is:

$$D_{RCM} = \frac{1000}{1.25 \cdot TEM} \tag{2}$$

To determine the D_{RCM} of 6 mixtures the following empirical relationship has been used:

$$D_{RCM} = A\left(w/b\right) + B \tag{3}$$

Table 1: Constants A and B for 2 cement types for equation 3

Cement type	*A*	*B*
CEM I	125	-42
CEM III	12.5	-1.6

Both formulas were obtained from the CUR Leidraad 1 [8].

For the following 6 mixtures the D_{RCM} were determined based on the conductivity and based on the empirical formula with:

$$\sigma = \frac{1}{TEM} \tag{4}$$

Table 2: D_{RCM} determined with the conductivity the empirical formula

Cement type	Water binder ratio	D_{RCM} formula 2 (10^{-12} m²/s)	D_{RCM} formula 3 (10^{-12} m²/s)
CEM III	0.45	9.20	4.03
CEM III	0.50	9.68	4.65
CEM I	0.60	27.24	33.00
CEM I	0.45	16.78	14.25
CEM III	0.37	4.96	3.03
CEM III	0.37 (lower strength class)	4.83	3.03

In figure 5 it is shown that the values obtained by both methods correlate rather well. These preliminary results, in combination with results from literature indicate that the conductivity can be used as an indicator for the durability of concrete in relation with chloride ingress.

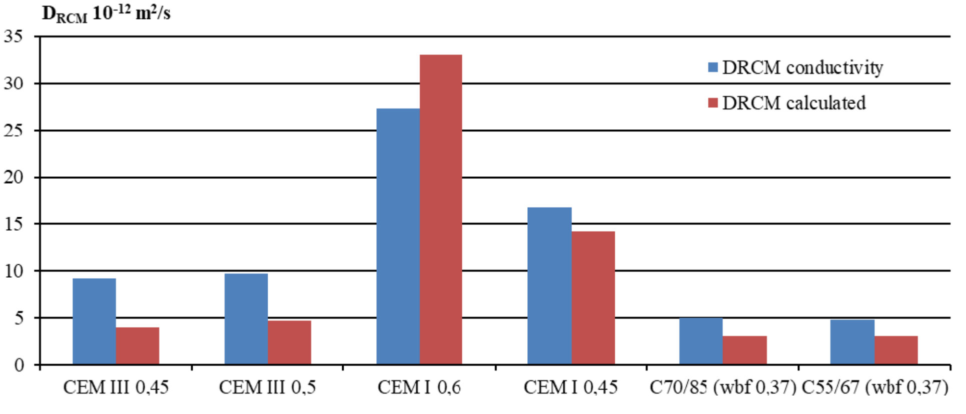

Figure 5: Correlation between calculated diffusion coefficient and diffusion coefficient based on the electrical conductivity of concrete at an age of 28 days

4.2 ***Electrical conductivity to detect ion ingress***

One of the factors influencing the electrical conductivity in concrete is the presence of ions in the pore water [9]. During the hardening phase of young concrete these ions mainly find their origin of the cement itself. The ions can also have an external origin. Concrete structures near the sea and structures that come in contact with de-icing salt have chloride ions in the cover. These chloride ions influence the conductivity of the concrete as shown by Spiesz [10] In his paper it is also concluded that this might be a way to use the electrical conductivity of concrete as an indicator of the presence of chloride ions.

Also sulphate has an effect on the electrical conductivity of cement pastes. It was shown by Hassan [11] that the conductivity of cement paste mixed with sulphate showed an increase of the conductivity not only after mixing but also after 400 minutes.

McCarter [12] showed that using the electrical conductivity measurements in the cover zone is a good way to monitor the changes in wetting-drying and ion ingress. The information obtained during monitoring can be used as an indicator for the risk of corrosion of steel reinforcement.

*4.3 **Discussion on durability***

Both chloride diffusion and ions present in the pore system can be detected using the electrical conductivity. The chloride diffusion detection finds its origin in the relation between microstructure and the electrical conductivity. If pores are blocked the permeability of the cement matrix will be lower compared to a matrix with an open pore structure. The presence of ions in the pores will increase the conductivity of the pore water and thus the conductivity of the cement matrix. It should be noted that in practice both phenomena can take place simultaneously. It will then be more complex to determine the source of the changes in the conductivity. Other important factors that influence the measurements are the ongoing hydration of the cement and the carbonation. Both change the microstructure and thus the conductivity of concrete [13]. These two factors also have a relationship with the durability of concrete.

Taking these considerations into account and by using models that describe the microstructure and its effect on the electrical conductivity it should be possible to use the electrical conductivity as a durability indicator. This is also presented by Weiss, at the 4th International Conference on Service Life Design for Infrastructures in 2018 [21], who uses the formation factor to link conductivity measurements to the chloride diffusion.

5 Electrical conductivity and setting time

As described before the conductivity of concrete will increase in the first hours after mixing. This is related to the increase of ions in the pore water. As soon as the concrete starts to set the decrease of the amount of pore water and later the loss of connectivity in the pore structure will dominate the conductivity of the overall electrical conductivity.

The electrical conductivity has thus a relation with the setting of concrete. This has been researched by Hossein Sallehi [14]. In this article called 'Characterization of Cement Paste in Fresh State Using Electrical Resistivity Technique' it was shown that the conductivity of the mixture of water and cement follows several phases which can been identified using electrical conductivity measurement.

In the first phase after mixing the ion concentration in the pore solution will increase rapidly.

In the second phase the ion concentration remains high and relatively constant or, often, still increases slightly. At the end of this period the conductivity will start to decrease slightly. This phase corresponds with the initial setting time.

In the third phase the formation of the pore structure will have a dominant influence on the overall conductivity of the cement matrix. The pore water will remain highly conductive, but the overall conductivity will decrease over time due to the reaction between water and cement which will increase the solid phase and decrease the amount of free pore water. This period ends as soon as the final setting time is over. From this moment onwards a load bearing microstructure is formed, and the strength development will start. In the fourth period the amount of pore water will decrease further and more pores are blocked, and the electrical conductivity will start to decrease rapidly.

The relationship between setting time and electrical conductivity is not only seen for OPC concrete but also in the early hydration of alkali-activated slag [15]. Also, the ConSensor is used to describe the setting time by Milenković [16] in which the same relationship between changes in conductivity and initial and final setting tine were found. In figure 6 two examples of setting times monitored with the ConSensor are presented.

The relationship between setting time and conductivity is also found by combining NMR measurements with conductivity measurements at the Technical University Eindhoven by Raheleh Pishkari an Leo Pel. Also the temperature was measured to take the temperature effects into account. The measurements were done on CEM III/C 32,5 N-LH/SR cement with a water cement ratio of 0.5 In one mixture demineralised water was used. In the other mixture salt was added (1 molal). This will speed up the hydration process which is indeed visible in the measurements of both the conductivity as the NMR. These preliminary results show that there is a relationship between the drop in conductivity and the drop in the signal of the NMR measurements.

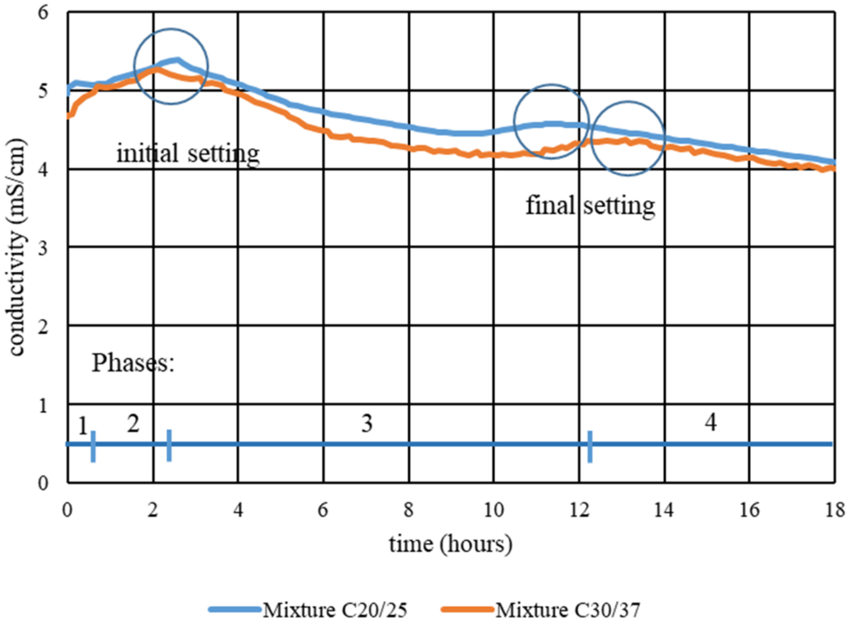

Figure 6: Initial and final setting time observed with the electrical conductivity for 2 concrete mixtures

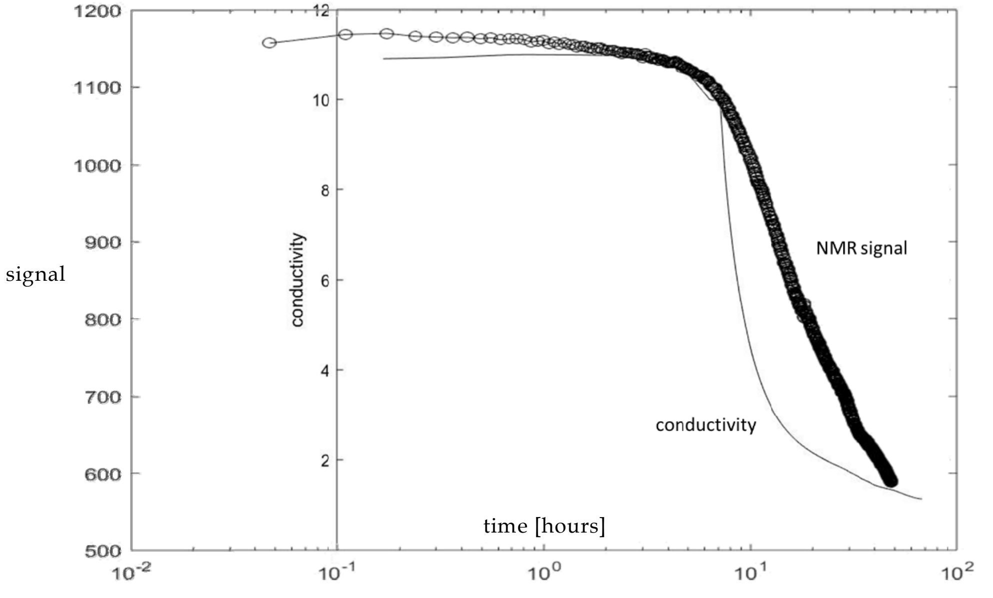

Figure 7: Similarities and differences in NMR signal and conductivity [mS/cm]

The signal of the NMR is mainly affected by the free ions in the pore solution [23]. The conductivity is not only influenced by the free ions also by the blocking of the pores. At the setting stage there is no blocking of pores present and the drop in conductivity and the drop in the signal of the NMR shows a similar behaviour as can be seen in figure 7 in which the measurements of the cement without salt of both the signal and the conductivity were compared.

The resemblances in the shape of the curves show that the drop in conductivity is most likely a result of the start of the setting of the cement. More tests have to be done to see if this relationship could be used for further identification of the setting time.

6 Temperature and electrical conductivity

6.1 Mature concrete

Tests in a laboratory are normally done at a constant temperature of 20 degrees Celsius. If the electrical conductivity is measured on-site the temperature of the concrete will vary in time. Both the ambient temperature and the heat production due to the hydration of cement will cause temperature fluctuations. The electrical conductivity of materials is influenced by the temperature. The electrical conductivity will change 3% per degree Kelvin for saturated matured concrete and 5% per degree Kelvin if the concrete is dry [13]. Similar temperature effects were found by Sallehi [14]. The temperature coefficient is defined as:

$$\frac{d\sigma}{\sigma_{ref}} = \alpha\, dT \qquad (5)$$

In which:

$d\sigma$	difference in conductivity (mS/cm) at a temperature dT (Kelvin)
σ_{ref}	conductivity at reference temperature
dT	change in temperature
α	temperature coefficient

The general background of the temperature dependency is based in the mobility of ions in the pore solution. This effect can be described with a Arrhenius based formula [17]:

$$\sigma_{Tref} = \sigma_T \cdot \exp\left[\frac{E_a}{R_g}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] \quad (6)$$

In which:

σ_T sample conductivity (mS/cm) at temperature T (Kelvin)

σ_{Tref} sample conductivity (mS/cm) corrected to the reference temperature T (Kelvin)

T temperature (Kelvin)

T_{ref} reference temperature (Kelvin)

E_a activation energy (J/mol)

R_g Universal Gas constant 8.3145 J/(mol K).

6.2 *Young concrete*

The normal way to determine temperature coefficient or activation energy is by varying the temperature and to measure the changes in the conductivity. For young concrete it is harder to determine the activation energy or a temperature coefficient. When the concrete is young the ongoing hydration will influence the conductivity as well. McCarter [18] showed that for concrete with Portland cement the activation energy can for example change from 22.6 kJ/mol at 7 days to 24.5 kJ/mol at 28 days. For concretes made with granulated blast furnace slag and fly ash hardly any change in the activation energy was observed. The total range of activation energy levels found by McCarter was: 17,8 – 29,8 kJ/mol depending on age, water cement ratio and type of cement.

6.3 *Temperature effect observed by ConSensor*

From the beginning of the development of the ConSensor, the effect of the temperature on the conductivity has been a point of attention. Therefore, an important part of the research activity was spent on finding temperature coefficients of 16 concrete mixtures. Temperature coefficients were observed in a range between 1 and 3.5%. Most data to determine these values were obtained from measurements at temperatures between 15 and 25 degrees Celsius and from young concrete. Also, for a wider range of temperatures: 10 – 50 degrees Celsius a temperature coefficient for a Portland cement-based concrete mixture of 3% was observed [19].

6.4 *Discussion on temperature*

Figure 8 shows the comparison between the effect of temperature on the conductivity calculated with the Arrhenius function and calculated with a temperature coefficient. Most important conclusion drawn up from this figure is that the right value for the temperature coefficient or the activation energy should be obtained from measurements. Then the differences between the 2 methods are rather small. This is for example shown by comparing the relation between temperature and electrical conductivity based on an activation energy of 17.8 kJ/mol and based on a correction factor of 3.5% in figure 8.

7 Conclusions

In a complex system like hydrating cement, with a changing microstructure and chemical composition in time, the electrical conductivity can be used to gain a lot of information about the concrete. Due to the many factors that influence both the electrical conductivity as the parameters of concrete a good understanding and a lot of experience is required before useful information can be gained. The 24 years of experience in using the ConSensor as a sensor to follow the concrete strength development has resulted in a lot of knowledge. This knowledge was not only about the relationship between conductivity and strength and how to use this in practice. Also, knowledge about the effect of temperature on the electrical conductivity was gained. This knowledge made the use of the electrical conductivity for strength development even more reliable.

With the increase of knowledge also other monitoring possibilities based on the electrical conductivity have been considered [20]. The relationship between electrical conductivity and chloride diffusion seems promising for durability analyses. And in the early stage just after mixing the electrical conductivity can be used as an indicator for the setting time.

By using material models combined with actual measurement data it is possible to get a substantial amount of useful information out of conductivity measurements. This information can be used for quality management of concrete both in the laboratory and on-site.

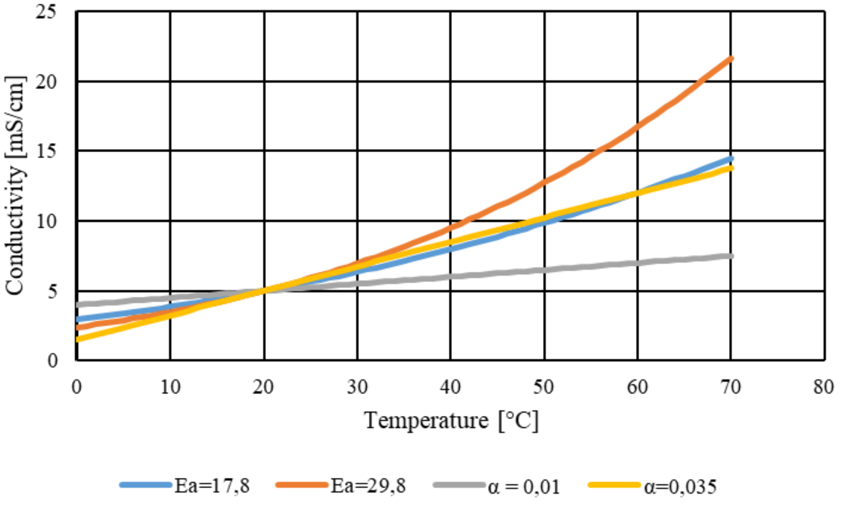

Figure 8: Effect of temperature on the conductivity of 5 mS/cm at a reference temperature of 20 degrees Celsius calculated with Arrhenius function and with a temperature correction factor

Literature

[1] Hilhorst M.A., *Dielectric Characterisation of Soil* (Ph.D. Thesis, Wageningen, 1998).

[2] Beek van A., *Dielectric properties of young concrete* (Ph.D. Thesis, Delft, 2000).

[3] Liang, Zeng, Zhou, Qu and Wang, A new model for the electrical conductivity of cement-based material by considering pore size distribution, *Magazine of Concrete Research*, Volume 69 Issue 20 (2017), 1067–1078.

[4] Backe K.R., Lile O.B., and Lyomov S.K., Characterizing Curing Cement Slurries by Electrical Conductivity, December, *SPE Drilling & Completion* (2001) 201-207.

[5] Breugel K. van, *Simulation of Hydration and Formation of Structure in hardening Cement Based Materials* (Ph.D. Thesis, Delft, 1991).

[6] Duracrete, Statistical Quantification of the Variables in the Limit State Functions (2000).

[7] Kiyfomi Kurumisawa, Toyoharu Nawa, Effect of Supplemental Cementitious Materials on Electric Conductivity and Chloride Ingress of Hardened Cement Paste, Fourth International Conference on Sustainable Construction Materials and Technologies, Las Vegas, USA, August 7-11, 2016.

[8] CUR Leidraad 1, Duurzaamheid van constructief beton met betrekking tot chloride-geïnitieerde wapeningscorrosie, Leidraad voor het formuleren van prestatie-eisen Achtergrondrapport (2011, in Dutch)

[9] Snyder K.A., Feng X., Keen B.D., Mason T.0., Estimating the electrical conductivity of cement paste pore solutions from OH-, K+ and Na+ concentrations, *Cement and Concrete Research*, Vol.-33, No.6, June 2003, 793-798.

[10] Spiesz P., Brouwers H.J.H., Application of the conductivity sensor as a chloride detector in concrete, 1st International Conference on the Chemistry of Construction Materials, Berlin, 7-9 October 2013, Monograph Vol. 46, 351-354, Ed. GDCh-Division of Chemistry of Construction Materials, Frankfurt am Main, Germany (2013).

[11] A.T. Hasan and S. Taha, The Effect of Sulfate on the Electrical Properties of Cement Pastes, *World Applied Sciences Journal* 19 (7) (2012) 957-961.

[12] McCarter, W. J., Chrisp, T. M., Staars, G., Basheer, M., & Blewett, J.. Field monitoring of electrical conductivity of cover-zone concrete. *Cement and Concrete Composites*, 27 (7-8), (2005) 809-817.

[13] Petrica Ionut I. Banea, Study of Electrical Resistivity of Mature Concrete, (MSc Thesis, 2015)

[14] Hossein Sallehi Characterization of Cement Paste in Fresh State Using Electrical Resistivity Technique (MSc Thesis, 2015)

[15] W.J. McCarter, T.M. Chrisp, G. Starrs, The early hydration of alkali-activated slag: developments in monitoring techniques, *Cement & Concrete Composites* 21 (1999) 277-283.

[16] Milenković N., Lecomteb J.P., Delsautec B, Delplanckea M.P., Staquetc S., Influence of silanes on the setting time and early age hardening of bulk hydrophobic mortars, 2nd International RILEM/COST Conference on Early Age Cracking and Serviceability in Cement-based Materials and Structures - EAC2 12–14 September 2017, ULB-VUB, Brussels, Belgium.

[17] Spragg R., Villani C., Snyder K, Bentz D., Bullard J.W., and Weiss J., Factors That Influence Electrical Resistivity Measurements in Cementitious Systems, Transportation Research Record: *Journal of the Transportation Research Board*, No. 2342, Transportation Research Board of the National Academies, Washington, D.C. (2013) 90–98.

[18] McCarter, W. J., Starrs, G., Chrisp, T. M., Basheer, P. A. M., Nanukuttan, S. V., & Srinivasan, S. Conductivity/activation energy relationships for cement-based materials undergoing cyclic thermal excursions. *Journal of Materials Science*, 50(3) (2014) 1129-1140.

[19] Veen van der M.A., Dielektrisch meten aan beton, (MSc Thesis in Dutch, 2003).

[20] Michelle R. Nokken and R. Doug Hooton, Electrical Conductivity Testing A prequalification and quality assurance tool, *Concrete international*, October 2006, 58-63.

[21] W. Jason Weiss, Burkan O. Isgor, Vahid Jafari Azad, and Chunyu Qiao, examining how pore solution chemistry impacts durability tests methods, specifications, and service life methods, Proceedings of the 4th International Conference on Service Life Design for Infrastructures, 27-30 August 2018 – Delft, Netherlands, p. 4.
[22] A. van Beek and M.A. Hilhorst, Dielectric Measurements to Characterize the Microstructural Changes of Young Concrete, *HERON*, Vol. 44 (1999) No. 1, pp. 3-17.
[23] R. Pishkari, L. Pel, M. Van Soestbergen & O.C.G. Adan, NMR study of salt transport in porous material during steady state wick action, IALCCE 2016, Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure (2016), 855-859.