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REAL-TIME CHLORIDE DIFFUSION COEFFICIENT IN CONCRETE USING EMBEDDED RESISTIVITY SENSORS

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Abstract

Service life of concrete infrastructure is severely compromised because of chloride-induced corrosion and measuring the chloride content is crucial to determine the remaining service life. DuraCrete provides a chloride ingress model based on Fick's 2nd law. Although the diffusion coefficient is modelled as a time-dependent variable, the DuraCrete solution averages it to a constant value. This simplification leads to inaccurate estimation of the chloride content. A new analytical solution that addresses the underlying mathematical discrepancy has been proposed. However, the time-dependent diffusion coefficient is still based on an empirical factor. In this study, a real-time durability monitoring system has been developed using remotely operated resistivity sensors. Such a system is able to monitor the time dependent diffusion coefficient without the need to incorporate empirical factors. Additionally, a numerical technique to find an approximation of the proposed improved analytical solution is presented using real-time resistivity measurements from laboratory and real structures. The results show that the discrete sensor data measurements over time provide a good approximation of the proposed analytical solution. The system developed in this study is used as a data-driven input parameter to supplement the existing chloride models.

Keywords: Real-time resistivity sensors, time-dependent chloride diffusion coefficient, DuraCrete, service life monitoring, concrete durability.

1. INTRODUCTION

Chloride-induced corrosion is arguably one of the most common degradation mechanisms that affects the durability and consequently the service life of concrete infrastructure. The ingress of chlorides in concrete can lead to pitting corrosion, spalling of concrete and an eventual structural failure. Thus, monitoring chloride ingress is crucial for estimating the service life. The current practice of condition assessment is by visual inspections which often miss the early corrosion symptoms. Other techniques often involve drilling concrete cores to measure the chloride profiles and the chloride diffusion coefficient [1]. DuraCrete provides guidelines to a probabilistic method to design a structure for a designated service life [2].

In DuraCrete, the models to predict the ingress of chlorides in concrete are based on the Fick's 2nd law of diffusion. The solution to determine the chloride ingress assumed the diffusion coefficient to be a constant parameter [3]. However, the time dependency of diffusion coefficient has been reported by many publications [4, 5] and an attempt is made to incorporate this in the DuraCrete model. Some mathematical discrepancies were reported pertaining to the inclusion of time-dependent diffusion [6,7]. Therefore a re-derived analytical model for chloride ingress is used in this study [8].

The aforementioned prediction models still heavily depend on the early age Rapid Chloride Migration (RCM) test and empirical ageing coefficients to model the time-dependency of diffusion coefficient. Making predictions based on a single input from a laboratory test may not give reliable predictions in the long term. Additionally, performing rapid chloride test is laborious and expensive. The idealised functions used in the models are not able to capture the effects due to varying environments in real structures. Electrical resistivity of concrete has been reported in the literature as a key parameter for concrete durability [9, 10]. In the past researchers have tried to correlate the electrical resistivity of concrete to chloride migration coefficient as an alternative to the RCM test [11, 12]. In this study, the sensor technology using electrical resistivity is used not only to determine the chloride migration coefficient but also as a monitoring tool to supplement the aforementioned models with a realistic dataset.

2. THEORETICAL BACKGROUND

Chloride transport in a porous medium like concrete is strongly dependent on the microstructure and its underlying permeability. The most widely known equation to model the chloride transport is based on the solution to the Fick's 2nd law of diffusion. The solution of Fick's 2nd law as presented by Collepardi et al.[3] is presented in Eq. 1.

$$C(x,t) = C_s - C_s.\operatorname{erf}\left\{\frac{x}{2\sqrt{D.t}}\right\} \tag{1}$$

Where, C_s is the surface chloride concentration assumed to be a constant value. In Eq. 1, the diffusion coefficient, D, is the constant of proportionality. D is indicative of the ability of concrete to transport chloride ions via diffusion. It was shown experimentally that the diffusion coefficient is a time dependent phenomenon and decreases with time [5, 13]. In the DuraCrete model, this time-dependency has been modelled as shown in Eq. 2 [2].

$$D(t) = D_0.\left(\frac{t_0}{t}\right)^{n_{cl}} \tag{2}$$

Where, t_0: reference time; 28 days, n_{cl}: ageing factor determined empirically and D_0 = RCM coefficient at reference time t_0. D_0 for modelling the time-dependent diffusion coefficient is based on RCM concept developed as an accelerated non-steady-state chloride migration test and standardised as NT Build 492 [14]. The time dependent-function as seen in Eq. 2 has been directly substituted in the solution presented in Eq. 1 which results in Eq. 3 and does not satisfy the Fick's 2nd law of diffusion. This erroneous substitution by DuraCrete is partially compensated using an empirical factor 'K_{tot}'. This mathematical discrepancy has been acknowledged in many studies [6–8].

$$C(x,t) = C_s - (C_s - C_i).\operatorname{erf}\left\{\frac{x}{2\sqrt{K_{tot}.D_0.\left(\frac{t}{t_0}\right)^{n_{cl}}.t}}\right\} \tag{3}$$

Where, $C(x,t)$ = chloride content at x depth and time t, and C_i= initial chloride content. This results in an over-simplification. The diffusion coefficient in Eq. 3 is treated as a constant at a particular instance in time. This results in an averaged value of the instantaneous diffusion coefficient over the whole service life giving erroneous estimations. A mathematically appropriate way of approaching the problem was presented by Gaal [6]. This required re-solving the differential equations as proposed in [15] but with a time-dependent diffusion coefficient function modelled as per Eq. 2. This resulted in an evaluation of a definite integral of the diffusion function $D(\tau)$ over time, see Eq. 6. A generalised solution is presented by Tang and Gulikers [8]. The solution takes into account the history of diffusion coefficient and provides an analytical solution that satisfies Fick's 2nd law, presented in Eq. 4-5.

$$C(x,t) = C_{s,0}\mathrm{erfc}\left\{\frac{x}{2\sqrt{T(t)}}\right\} \tag{4}$$

$$T(t) = \int_{t_{ex}}^{t+t_{ex}} D(\tau)d\tau = \frac{D_0}{1-n_{cl}}.\left[\left(1+\frac{t_{ex}}{t}\right)^{1-n_{cl}} - \left(\frac{t_{ex}}{t}\right)^{1-n_{cl}}\right]\left(\frac{t_0}{t}\right)^{n_{cl}}.t \tag{5}$$

Here, t_{ex} is the concrete age at first exposure to chlorides. The model is simplified further by assuming $t \gg t_{ex}$ which implies $t_{ex} \approx 0$. This reduces the model further to Eq. 6.

$$T(t) = \int_0^t D(\tau)d\tau = \frac{D_0}{1-n_{cl}}.\left(\frac{t_0}{t}\right)^{n_{cl}}.t \tag{6}$$

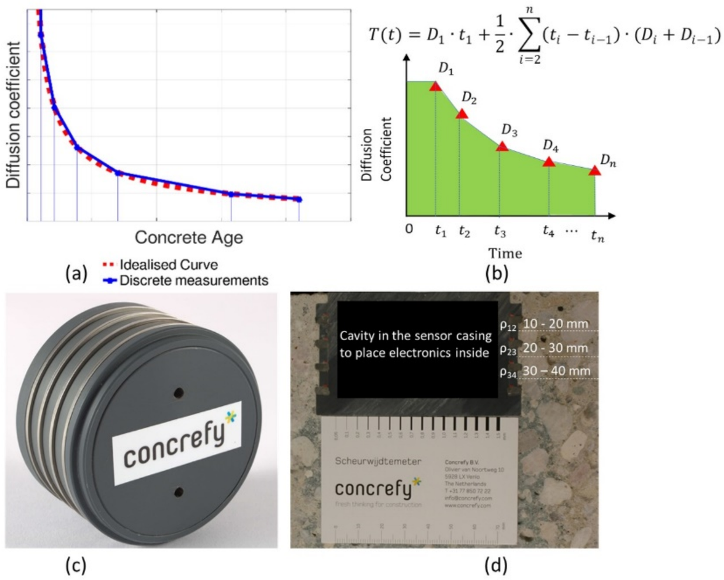

Figure 1: (a) Discrete data schematic (b) Concept to evaluate the area under the curve by trapezoidal rule (c) Durability sensor (d) Cross-section of the durability sensor.

The electrical resistivity is a parameter that is closely associated with the ionic transport of species in concrete. It can be correlated to the moisture content and tortuosity of concrete microstructure [9]. The chloride ingress models need RCM coefficient as an input. The test is time intensive. As an alternative, researches have proposed electrical resistivity to evaluate the RCM test with success. As a part of Brite EURam III, different resistivity methods were compared with the RCM test results conducted in the laboratory and a good correlation was found [11]. The resistivity and the RCM coefficient are inversely proportional under saturated conditions with similar regression coefficients [9, 12, 16–18]. Under non-saturated conditions, resistivity was proven to be a good indicator of diffusion [19].

In this study, electrical resistivity is used as a parameter to evaluate the time-dependent diffusion coefficient by providing real-time data. For this purpose, a multi-ring impedance sensor is developed at Concrefy that remains embedded in concrete and send resistivity data remotely. The correlation based on DuraCrete [11] is used to relate electrical resistivity measured in concrete using embedded sensors to RCM. The obtained diffusion coefficient from the resistivity measurements is combined with Eq. 4 and Eq. 6 to evaluate chloride ingress in concrete. In Eq. 4 a new term $T(t)$ was introduced as a correction to the DuraCrete model and integrated in Eq. 6. Since $D(\tau)$ can be described as a continuous function modelled using an ageing coefficient, it was possible to evaluate a definite integral. However, resistivity measured by the sensors results in a set of discrete points in time. Thus, an integration over the time domain is undefined. The variable $T(t)$ is the area under the diffusion-time curve presented in Eq. 2. The data points can be used to approximate $T(t)$ by discretising them further as trapezoids, see Fig. 1a. The scheme to approximate $T(t)$ is presented in Fig. 1b. The discrete points are marked in red which measure D_i at time t_i. The vertices of the points serve as boundaries for trapeziums. The approximation of $T(t)$ is thus a cumulative sum of the discrete trapeziums as seen in Fig. 1 b. The function is updated for every new measurement in time. The applied numerical technique is called 'Trapezoidal-rule'.

3. EXPERIMENTAL

The schematic of the real-time durability sensor and its cross-section is shown in Fig. 1c and d. The sensor has four stainless steel rings 10 mm apart with a geometric constant of 0.2 and excitation frequency of 108 Hz. The resistivity is measured at 3 zones within the concrete cover depth as shown in Fig. 1d. For the evaluation of diffusion coefficient in DuraCrete, the resistivity of Two Electrode Method (TEM) is used. The DuraCrete also reported the correlation between the multiple-ring electrode (MRE) sensors and the TEM method. The resistivity of TEM was found to be 1.07 times as the MRE with negligible variance [11]. This implies that the TEM-MRE correlation can be directly applied. The experiment involves regular resistivity measurements and translating them to diffusion coefficients. The measurements are obtained in the laboratory conditions as well as an engineering structure used in the case study.

Table 1: Concrete mix design and properties for lab experiments

Mix Tag	Binder type	Binder Content (Kg/m^3)	w/b	Exposed Environment	$D_{RCM\ @\ 28\ days}$ [x10^{-12} m^2/s]	Ageing Coefficient [n_{cl}]
I	CEM I	400	0.4	95% RH, 20ºC	11	0.3 [2]
II	CEM III/B	340	0.48	95% RH, 20ºC	10.8	0.71 [2]
III	CEM I	280	0.65	95% RH, 20ºC	33	0.3 [2]
MG	CEM IIB-S+CEM IIA-S	340	0.5	Atmospheric	10	0.65 [12]

Three different mixes were prepared by changing the binder type as well as the water-binder (w/b) ratio. The details of the mix are presented in Table 1. CEM I and CEM III/B were used since they are the most prevalent binder types in the Netherlands. Concrete was cast for the purpose of sensor measurements and for evaluating the standard RCM coefficient. For every mix, 3 cubes were casted in situ with embedded sensors and 3 cubes were cast without sensors.

The cubes were cast in the laboratory and maintained in the climate room at 95% RH and 20 °C condition. Mix MG was cast on the construction site as part of the case-study bridge in Mönchengladbach, Germany. Sensors were embedded in the bridge. The sensor installation is presented in Fig. 2a and b.

The diffusion coefficient derived from resistivity measurements are compared with the time-dependent idealised curve used in chloride ingress models, presented in Eq. 2. The idealised curves depend on the RCM coefficients at a reference age of 28 days and the ageing coefficient (n_{cl}) adopted from DuraCrete [2]. RCM test is conducted as per [14]. Submerged condition is assumed since it was closest to the condition in the climate room. For the casestudy, n_{cl} is adopted from CUR-81 for the specific binder type that was used [12]. The parameters are presented in Table 1.

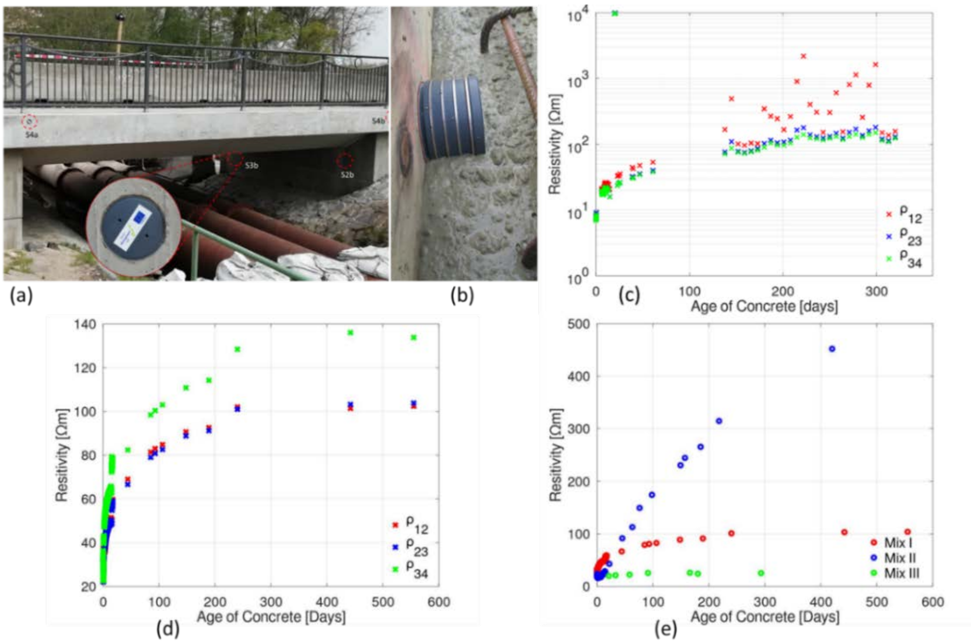

Figure 2: (a) and (b) Durability sensor in a bridge from the case study (c) Resistivity measurements of sensor from the case study (d) Resistivity measurements of Mix I at three depths in the climate room (e) Comparison of the resistivity measurements.

4. RESULTS AND DISCUSSION

The results of the resistivity measurements in the lab and the case-study are presented in Fig. 2. In Fig. 2c, the resistivity at the top zone (ρ_{12}) is relatively different than the resistivity at the inner depths (ρ_{23} and ρ_{34}). The top surface is sensitive to the environmental changes compared to the inner layers and thus exhibits different transport properties compared to the internal layers as seen in Fig. 2c. This is called 'skin effect' and is one of the reasons for inaccuracies while modelling chloride transport using Fick's second law of diffusion [20]. In this study, the diffusion coefficient is calculated based on the average across the depth. This partially captures the skin effect and its role in the transport properties of concrete. The electrical resistivity of concrete is related to its degree of saturation [21]. Thus, monitoring electrical resistivity provides insights in the transport properties. This dependency is visible in Fig. 2d (see ρ_{12}) which results in steady resistivity values for a wet environment and Fig. 2c where the drier environment results in an increasing resistivity (see ρ_{12}). The continuous monitoring of the resistivity is also able to capture the fluctuations in the transport properties arising from the changes in the ambient RH. Moreover, the electrical resistivity shows a strong dependence on the type of binder as seen in Fig. 2e.

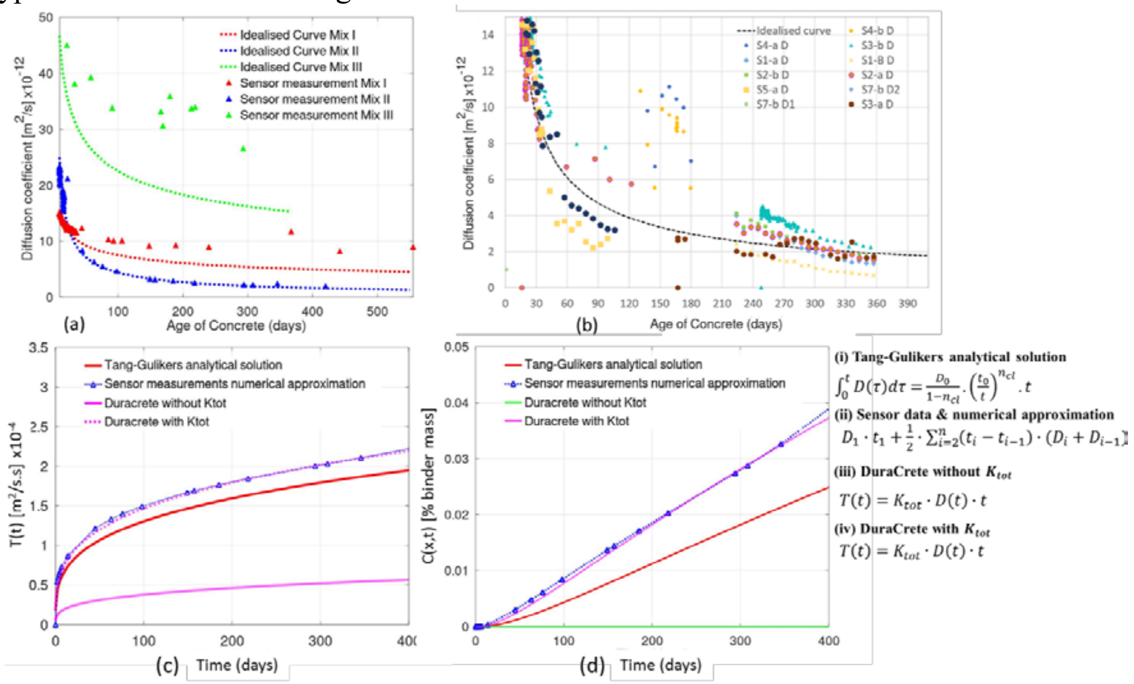

Figure 3: (a) Comparison of the diffusion coefficient measured by the sensors in the lab conditions (b) Diffusion coefficient measured in the case-study (c) Comparison of different approaches to evaluate T(t) (d) Comparison of chloride content calculation.

The results for the diffusion coefficients using sensor measurements in the lab as well as case-study are presented in Fig. 3a and b. These are compared against their respective idealised curves. The sensor results are in case of Mix I and Mix II. Both the mixes are composed of different binder types as well as water-binder ratios. In spite of different chemical compositions, the sensor results are able to correspond to the ideal curves. As a result, a mix-specific calibration is not necessary. The real-time data thus provides better insights in the ageing and offers a possibility to monitor transport properties without a need to incorporate an empirical ageing factor. Moreover, the diffusion coefficients calculated from the case study as presented in Figure 3b are also comparable to its respective idealised curve. The low scatter results from the variation in local concrete properties and the environment. The bulk results still lie in an acceptable range. The measurements do not correspond to the idealised curve when it comes to Mix III. Mix III has a higher w/b ratio compared to Mix I. Possibly, Mix III forms a microstructure with a high pore connectivity resulting in a much higher diffusion coefficient compared to the idealised curve. It is plausible, water-binder ratio is not taken into account while modelling the idealised curves.

A comparison of different approaches to estimate chloride content is carried out. Different approaches differ in the calculation of the variable $T(t)$. This is elaborated in Fig. 3d. The analytical solution by Tang and Gulikers is used as a reference [8] (see Eq. 6). Mix II data is presented for comparison. It can be inferred from Fig. 3c that the sensor measurements evaluated using numerical approximation slightly overestimate the analytical solution. However, they are comparable. The deviation occurs only in the initial stages because of large time steps in the sensor measurements. However, after the initial deviation, the slope of the analytical solution and the approximation using sensors remains similar. This implies the error does not accumulate over time. The initial deviation can thus be overcome by assigning shorter time steps in the initial period.

From Fig. 3c, it is also evident that the DuraCrete model without the factor K_{tot}, underestimates $T(t)$. This is because at every instance of time this approach approximates $T(t)$ to a rectangle using the diffusion coefficient at a particular time t. The diffusion coefficient is averaged over the entire time period without taking into account the history of diffusion coefficient. This results in an underestimation. The error increases with each time step. However the rate of error decreases with each time step since the long term diffusion coefficient tends to a constant value. Over the service life of a structure, the error may not be significant. However, it is quite significant in the first few years and thus cannot be used for monitoring. DuraCrete compensates this error by introducing an empirical factor K_{tot}. With that, the DuraCrete model comes close to the analytical model. However, the underlying mathematical lapse is not addressed. The introduction of an empirical factor is flawed as the solution is not generalised. As the error accumulation decreases in time, inclusion of a constant factor in the long would result in an overcompensation making the service life model too conservative.

Having calculated *T(t),* the chloride content is calculated as per Eq. 6 where $T(t)$ is defined and the result presented in Fig. 3d. The sample calculation assumes the parameters listed for Mix II in Table 1; $C_{s,0}$=2.2 % of the binder weight; K_{tot}=3.88 based on DuraCrete; Cover depth=50 mm. It is evident that DuraCrete without the K_{tot} factor underestimates chloride ingress. The error between the analytical model and measurements is due to the early deviation.

5. CONCLUSIONS

Embedded durability sensor using remote real-time resistivity measurements is shown to estimate the changing diffusion coefficient of concrete irrespective of the type of binder and without defining an empirical ageing coefficient. As a result, additional calibrations may not be required thereby providing a generalised approach. The sensor results were comparable to the laboratory as well as the full-scale case study. These measurements capture local variations in diffusion coefficient due to changes in the ambient conditions contrary to the current modelling practices. Thus, the sensor technology offers a potential to overcome some modelling limitations by providing a realistic dataset. Integrating sensor data to the existing chloride ingress models require some modifications. This is achieved by employing a numerical method to approximate the analytical solution using sensor readings as an input parameter. This method is able to provide a comparable approximation in relation to the time-dependent analytical model mentioned in the literature. The mathematical discrepancy in the DuraCrete approach in relation to the time-dependent diffusion coefficient and its potential overcompensation due to the use of a constant empirical factor K_{tot}, is also discussed. A deterministic approach is followed as a first step to develop the methodology. However, owing to the potential of significant data collection, spatial variation in diffusion properties can be included in the model. Subsequently, the model can be extended to a robust probabilistic model. Finally, to conclude, the data-driven approach presented in this study is a significant step towards development of a valuable tool that can extend the existing chloride ingress models.

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