

# Investigation on the effectiveness of the repair method 8.3 “Corrosion protection by increasing the electrical resistivity” in chloride-containing concrete

## Part 2: Chloride redistribution in concrete after application of a system sealing surface protective coating

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Dedicated to Professor Dr-Ing. Michael Raupach on the occasion of his 60<sup>th</sup> birthday

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### Abstract

This DFG-funded research project aimed to gain a better understanding of the mechanisms of the W-Cl repair principle within the framework of fundamental investigations, to contribute to the creation of the necessary basis for a broader application of the repair principle in practice. The focus was on the development of a model to describe the chloride redistribution after the application of a system sealing surface protective coating. On the basis of Fick's second law of diffusion, a mathematical model with a self-contained analytical solution was developed, with the help of which the chloride redistribution after application of a system sealing surface protective coating can be calculated under the idealized assumption of complete water saturation of the concrete. Furthermore, the influence of the dehydration of the concrete, expected as a result of the application of the repair principle W-Cl, on the chloride redistribution was investigated. On the basis of laboratory tests and numerical simulations, material-specific reduction functions were developed to quantify the relationship between the chloride diffusion coefficient and the ambient humidity.

### KEYWORDS

chloride, chloride redistribution, reinforced concrete, repair method

## 1 | INTRODUCTION

Compared with conventional repair principles, the W-Cl repair principle represents a technically and economically interesting process for the repair of chloride-loaded concrete structures. The method is based on the reduction of the

water content (W) in the area of the chloride-contaminated concrete (Cl), which is achieved by applying a surface protective coating. The coating is intended to prevent the intermittent penetration of chlorides and moisture and to prevent the initiation of the reinforcement corrosion. Unresolved questions regarding the effectiveness of the

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process and the resulting application restrictions in the relevant regulations (such as in References [1,2] and in future as in Reference [3]) have so far made a practical and efficient application of the process hardly possible.

To enable a widespread and practical application of the W-Cl repair principle for chloride-loaded concretes, fundamental questions regarding the effectiveness of the process must be answered. One of the central questions is as follows: What are the effects of the application of a surface protection system on the corrosion behavior of steel in concrete and thus on the remaining service life of a component?

A prerequisite for chloride-induced corrosion of steel in concrete is the achievement of a component-specific, critical corrosion-inducing chloride content<sup>[4-6]</sup> at the level of the reinforcement layer. The quantification of the chloride redistribution in concrete after the application of a surface protective coating is the first approach to evaluate the effectiveness of the repair principle W-Cl and estimate the remaining service life after application of the method.

For this purpose, a mathematical model with a self-contained analytical solution was developed, with the help of which the chloride redistribution can be calculated without the need for special FEM software, assuming complete water saturation of the concrete after application of a system sealing coating.

Subsequently, the influence of the expected dehydration of the concrete due to the application of the repair principle W-Cl on the chloride redistribution in the sealed system was investigated. On the basis of the investigations carried out and the numerical calculations derived from them, material-specific reduction functions were developed, with the aid of which the dependence of the chloride diffusion coefficient on the moisture conditioning of the concrete can be described.

## 2 | CHLORIDE REDISTRIBUTION AT WATER SATURATION

### 2.1 | General information

By applying the surface protective coating to the concrete surface, the chloride entry into the concrete component is prevented. However, driven by the concentration gradient of the chlorides in the component, a redistribution of the chlorides in the concrete occurs after the application of the surface protection system. This process of diffusion-controlled concentration equalization leads to a decrease in the chloride concentration in the area close to the surface; however, an increase in the chloride concentration can be expected in deeper layers of the component. Depending on the given boundary conditions and the size of the concrete cover, the critical

corrosion-inducing chloride content may be exceeded at the level of the reinforcement, which may lead to the initiation of reinforcement corrosion.

### 2.2 | Model building

There are several mathematical models in the technical literature<sup>[7-11]</sup> that can be used to describe the chloride penetration process in concrete. In the most common analytical models, a purely diffusion-controlled mass transfer is assumed under simplified assumptions, whereby the chloride penetration process can be described with the use of a solution of Fick's second diffusion law derived by Crank.<sup>[12]</sup> As boundary conditions, a solution with a constant chloride content over the entire exposure period and a chloride-free concrete at the start of the observation period are assumed.

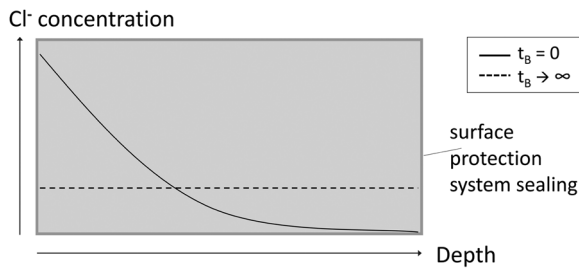
A first rough estimate of the chloride redistribution after the application of a surface protective coating was already presented by Dauberschmidt.<sup>[13]</sup> However, according to the current state of the art, there is no analytical mathematical model that can be used to describe the redistribution of chloride in the coating after the application of a protective surface coating. The existing calculation approach according to Breit et al.<sup>[5]</sup> for the description of the chloride penetration process cannot be applied because the boundary conditions change in the case of system sealing.

Celebi<sup>[14]</sup> derived an analytical calculation approach was derived to describe the chloride redistribution after the application of a surface protective coating. The following boundary conditions were assumed:

1. After coating (application of the surface protection system), the component is considered a completely "closed, sealed system." It is assumed that no new chlorides can be introduced into the concrete and that the chlorides already present in the concrete remain in their entirety.
2. For  $t \rightarrow \infty$ , a homogeneous distribution of the chlorides over the entire cross-section of the component is assumed.
3. The diffusion coefficient of the concrete is assumed to be constant and unchangeable over time for the period after the system sealing, lying on the safe side.

The boundary conditions specified for the derivation of the analytical calculation approach are visualized in Figure 1.

For the mathematical description of the chloride redistribution after sealing of the concrete, a purely diffusion-controlled mass transfer is assumed under simplifying assumptions, as with the already existing



**FIGURE 1** Visualized representation of the boundary conditions to derive an analytical calculation approach to describe the chloride redistribution

models describing the chloride penetration process. As the “sealing” of the component excludes an intermittent impact of chlorides, it can be assumed that the relevant transport processes can be described sufficiently precisely via the diffusion process.

To describe the diffusion process mathematically, a fully water-saturated state of the concrete is first assumed for the model development. Concerning the life expectancy prognosis or remaining service life, this assumption is on the safe side with regard to the later evaluation in practice, as a slowing down of the diffusion rate or the chloride redistribution is to be expected with concrete that is only partially saturated with water.

The relationship between temporal and local concentration differences can fundamentally be described by Fick’s second law of diffusion (1). Thus, the differential equation is suitable for the mathematical description of transient diffusion and can be used as a basis for the calculation of the time-dependent and depth-dependent chloride concentration, assuming a purely diffusion-controlled transport process

$$\frac{dc}{dt} = D \cdot \frac{d^2c}{dx^2}. \tag{1}$$

Depending on the initial and boundary conditions explained in the following, an analytical solution approach can be derived for the differential equation. The boundary conditions assumed, in this case, can be formulated mathematically as follows:

$$\text{BC1: } \frac{dc(0, t)}{dx} = 0, \text{ for } t > 0, \tag{2}$$

$$\text{BC2: } \frac{dc(L, t)}{dx} = 0, \text{ for } t > 0, \tag{3}$$

$$\text{BC3: } c(x, 0) = f(x). \tag{4}$$

The boundary conditions BC1 and BC2 describe that the derivative of the concentration  $c$  with respect to  $x$  is 0 for all

periods of observation at the edges of the considered interval ( $x=0$  component surface,  $x=L$  inner component boundary). This is the result of the fact that a complete sealing of the component is assumed by the application of the coating, and thus no chlorides can leave the system. Boundary condition BC3 expresses that the chloride concentration at the time of coating ( $t_b = 0$ ) can be described over the cross-section of the component using the function  $f(x)$ .

The following mathematical relationship is used to derive the analytical calculation model:

$$c(x, t) = c_1(x) \cdot c_2(t). \tag{5}$$

Inserting (1) into (5) results in an expression that is only dependent on  $t$  and  $x$ , and thus can be described as the constant  $k$ :

$$\frac{c_2'(t)}{c_2(t)} = D \cdot \frac{c_1''(x)}{c_1(x)} = k. \tag{6}$$

The following results through rearrangement of (6):

$$c_2(t) = e^{k \cdot t}, \tag{7}$$

$$c_1''(x) - \frac{k}{D} \cdot c_1(x) = 0. \tag{8}$$

Equation (8) is a second-order linear differential equation with constant coefficients ( $A$  and  $B$ ), which can be described as follows for the only relevant case without a trivial solution for  $\frac{k}{D} < 0$ , determined by a sign consideration:

$$c(x, t) = \left( A \cdot \cos\left(\sqrt{\left(-\frac{k}{D}\right)} \cdot x\right) + B \cdot \sin\left(\sqrt{\left(-\frac{k}{D}\right)} \cdot x\right) \right) \cdot e^{k \cdot t}. \tag{9}$$

Inserting the boundary conditions and deriving the function the following results, for  $n \in \mathbb{Z}$ :

$$k = -\left(\frac{n \cdot \pi}{L}\right)^2 \cdot D. \tag{10}$$

After inserting (10) into (9) and considering the boundary conditions, a solution of the differential equation is obtained:

$$c(x, t) = A \cdot \cos\left(\sqrt{\left(-\frac{k}{D}\right)} \cdot x\right) \cdot e^{k \cdot t}. \tag{11}$$

Considering the axial symmetry of the cosine function, the solution of the differential equation can be expressed by the following linear combination:

$$c(x, t) = p + \sum_{n=0}^{\infty} b_n \cdot e^{-\left(\frac{n \cdot \pi}{L}\right)^2 D \cdot t} \cdot \cos\left(\frac{n \cdot \pi}{L} \cdot x\right). \quad (12)$$

By inserting the boundary conditions, transforming the expression into a  $2L$ -periodic function in the form of a Fourier series, and then comparing the coefficients, the following is obtained:

$$p = \frac{1}{L} \left( \int_0^L f(z) dz \right). \quad (13)$$

By inserting (13) into (12) and taking into account the coefficients determined in the Fourier series, this is the result:

$$\begin{aligned} c(x, t_b) = & \frac{1}{L} \int_0^L f(z) dz \\ & + \sum_{n=0}^{\infty} \frac{2}{L} \int_0^L f(z) \cos\left(\frac{\pi \cdot n \cdot z}{L}\right) dz \\ & \cdot e^{-\left(\frac{n \cdot \pi}{L}\right)^2 D_{app,C} \cdot t} \cdot \cos\left(\frac{\pi \cdot n \cdot x}{L}\right), \end{aligned} \quad (14)$$

where  $c(x, t_b)$ , chloride concentration at depth  $x > 0$  after a duration of exposure  $t_b$  (wt%/c),  $L$  is total component depth (m),  $D_{app,C}$  is apparent chloride diffusion coefficient ( $m^2/s$ ) of concrete at observation time  $t_b = 0$  s,  $x$  is distance from the surface (m),  $t_b$  is period after component sealing (s), and  $f(z)$  is chloride distribution in concrete at the time of component sealing (wt%/c).

Equation (14) can be used to determine the depth-dependent chloride content in the concrete after the application of a system sealing coating as a function of time. The developed model with a self-contained analytical solution allows the calculation of the chloride redistribution without a special FEM simulation software.

### 2.3 | Verification of the model by comparative numerical calculations

To verify the developed analytical calculation model, the chloride redistribution in concrete after “sealing a closed system” was simulated in a finite element model using the COMSOL Multiphysics® software.

As with the modeling of the analytical approach, a purely diffusion-controlled transport mechanism and water-saturated state of the concrete were assumed for the numerical modeling in COMSOL. The calculation in the program was based on the differential equation of Fick's second law of diffusion. In accordance with the analytical approach, the numerical simulation was divided into two steps. First, the chloride profile was

determined as a function of the chloride solution present at the point in time immediately before system sealing ( $f(z)$ ). Then the system sealing was taken into account in the FEM model by adapting the boundary conditions, and the chloride redistribution was simulated as a function of time. The chloride profiles determined with the help of the FEM simulation are compared with the results of the analytical calculation in Figure 2.

It can be seen in Figure 2 that the chloride profiles of the numerical simulation match the chloride profiles of the analytical calculation exactly. From this, it can be concluded that the chloride redistribution in the concrete after “system sealing” can be described reliably and precisely with the help of the developed analytical model.

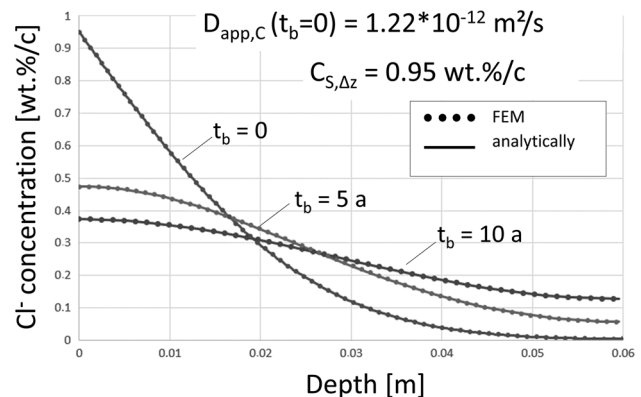
### 2.4 | Validation by laboratory tests

To evaluate the practical suitability of the developed model, laboratory tests were carried out, in which the chloride redistribution in the concrete was determined over time after “sealing the system.”

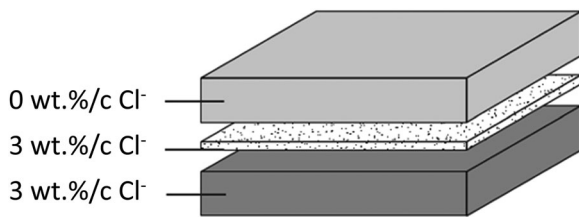
For this purpose, a two-layer test specimen structure with a chloride-loaded concrete and an initially chloride-free concrete was designed. The test specimen structure is shown schematically in Figure 3.

The concrete discs were first conditioned at 98% RH, then after reaching the equilibrium moisture content, they were electrolytically coupled by using a 5-mm thick layer of mortar, and then sealed to be almost water vapor tight by applying a two-component coating on polyurethane basis.

To determine the chloride redistribution after electrolytic coupling of the concrete discs, drill dust was extracted



**FIGURE 2** Chloride profiles as a result of chloride redistribution after system sealing—a comparison of the results of the FEM simulation and analytical calculation according to Equation (14)



**FIGURE 3** Schematic diagram of the electrolytic coupling of the chloride-free and chloride-containing concrete discs

from the initially chloride-free concrete disc at fixed time intervals and the resulting chloride profiles were created, where  $x = 0$  mm marks the transition to the mortar layer.

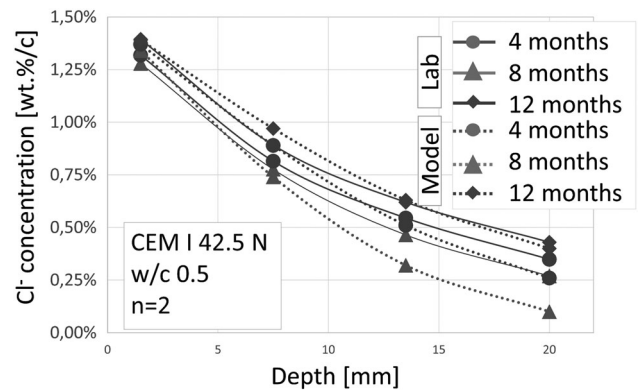
Figure 4 shows an example of a concrete produced with Portland cement CEM I (OPC) 42.5 N and a water-cement ratio  $w/c = 0.50$ . The chloride profiles determined in laboratory tests are compared with the calculated chloride profiles.

The chloride profiles determined in the laboratory test essentially correspond to the chloride profiles predicted in the mathematical model. The chloride concentrations predicted in the mathematical model tend to be higher than the values measured in the laboratory test and thus on the safe side regarding the estimation of the remaining service life.

Exceptions to this tendency are the elevated chloride concentrations in lower sample areas and the chloride profile determined in laboratory tests after a 4-month exposure period. The increased chloride concentrations after a short period of exposure and in the deeper sample layers are due to the test setup. During the electrolytic coupling of the individual concrete discs, additional moisture is introduced into the concrete via the cement-based bonding layer. As a result of the moisture gradient and the resulting moisture transport toward the core of the specimen, an accelerated chloride transport is briefly initiated. Within the course of the moisture equalization, the chlorides are accelerated for a limited period of time into deeper layers of the component via capillary chloride transport or “Huckepack transport.”

The test results show that the effects of short-term capillary chloride input are particularly noticeable during brief periods of exposure and become less significant with increasing exposure duration. To reduce the influence of “Huckepack transport,” a test series with a long-term exposure of test specimens with greater structural depth would, therefore, be advisable.

As the effect of “Huckepack transport” is caused by the experimental setup, this circumstance is not relevant for the practical application of the model for existing structures.



**FIGURE 4** A comparison of the chloride profiles measured on the initially chloride-free sample and the mathematically predicted chloride profiles

### 3 | CHLORIDE REDISTRIBUTION AT PARTIAL WATER SATURATION

#### 3.1 | General information

In principle, dehydration in concrete leads to an increase in chloride diffusion resistance, and thus to a slowing down of chloride redistribution in the structural element.

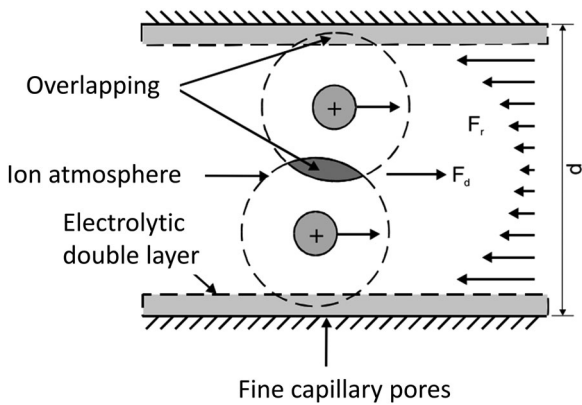
Initially, this is caused by the fact that the capillary pores empty with a decreasing moisture content and a thin film of water remains only on the surfaces of the pore walls. In this case, chloride diffusion can only take place via the remaining adsorbate layer on the pore wall surfaces.<sup>[11]</sup>

This causes the chlorides to interact more strongly with the pore surface. The chloride ions adsorb on the pore surface, which leads to a redistribution of the electrical charge. The resulting potential differences cause the formation of an electrolytic double layer, which acts as a kind of energy barrier at the phase transition between solid and solution and has a retarding influence on the ion transport (see Figure 5).

This so-called ionogenic pore-blocking effect consequently leads to a reduction of the chloride diffusion coefficient in partially water-saturated concretes.<sup>[15]</sup>

A further factor influencing chloride diffusion behavior is the increasing tortuosity that occurs when components dehydrate.<sup>[16]</sup> Tortuosity describes the degree of twisting of the transport paths in the pores of porous materials.<sup>[17]</sup> In general, the capillary pores represent the main transport path in the pore structure of concrete.

The pore structure shown in Figure 6 shows that chloride transport cannot take place directly through the concrete cross-section ( $L$ ), but it takes place along the pore structure via geometric detours depending on the pore structure ( $L_e$ ).



**FIGURE 5** Schematic diagram of the electrolytic double layer at the phase transition between solid and pore solution<sup>[15]</sup>

With partial water saturation, the probability that the pores are saturated with water and thus diffusion can take place to the full extent decreases with an increasing pore diameter in the concrete. The larger pores are first emptied, whereas the smaller pores are still saturated with water. By partially blocking the transport path, chloride diffusion takes place via a detour through the smaller pores, in which a greater degree of water saturation prevails, thus extending the average transport path of the chlorides in the concrete. This results in a decrease of the chloride diffusion coefficient, and thus a slowing down of the chloride redistribution in partially water-saturated concretes.<sup>[9,19]</sup>

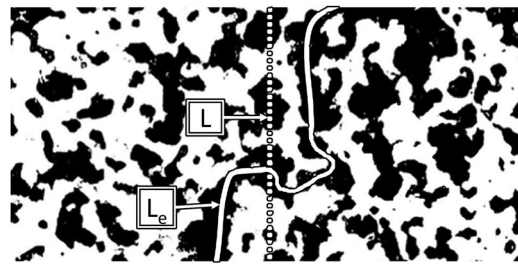
### 3.2 | Laboratory tests

The laboratory experiments aimed to determine the influence of moisture content on the chloride diffusion coefficient of concrete.

For this purpose, modified migration tests on test specimens with different moisture conditions are carried out following the BAW Code of Practice “Chloride penetration resistance of concrete.”<sup>[20]</sup> To prevent capillary water absorption and the associated “Huckepack transport” of chlorides, the test specimens were provided with an OS 4 coating, which prevents convective transport mechanisms but permits ion diffusion to a large extent.

In the laboratory tests, two concretes with different types of cement (CEM I [OPC] 42.5 N and CEM III [BFC] 42.5 N) were analyzed. The results of the migration tests are shown in Table 1.

The results of the RCM test confirm the effect described in the technical literature that an increased diffusion resistance occurs with decreasing moisture content of the concrete.<sup>[11,21–23]</sup> With the decrease in the



**FIGURE 6** Representation of the transport path in the pore structure of the concrete<sup>[18]</sup>

moisture content, the migration coefficients of the test specimens of the CEM I (OPC) concrete decrease relatively more than the migration coefficients of the test specimens of the CEM III (BFC) concretes.

However, the chloride migration coefficients listed in Table 1 do not describe the chloride penetration resistance of the concrete, but that of the composite system of concrete and the applied OS 4 coating. The comparison of the two water-saturated test series with and without OS 4 coating shows that the coated test specimens are characterized by a lower migration coefficient than the uncoated reference specimens. This is because the OS 4 coating allows diffusion but has a higher diffusion resistance than concrete.

To determine the actual chloride migration coefficients of the concrete and to derive a precise conclusion regarding the influence of the degree of moisture on the chloride diffusion in the concrete, the migration coefficients of the partially water-saturated concrete—independent of the influence of the applied surface protection system—were determined by means of a numerical simulation.

**TABLE 1** Chloride migration coefficients of the coated samples determined in the RCM test as a function of relative humidity

Specimen	Conditioning (% RH)	$D_{RCM}$ ( $10^{-12} \text{ m}^2/\text{s}$ )	Reduction factor
CEM I (OPC)	REF <sup>a</sup> 100	18.04	–
	OS 4 100	13.00	1.00
	OS 4 95	11.25	0.86
	OS 4 85	8.04	0.62
	OS 4 75	6.00	0.46
	OS 4 65	3.09	0.24
CEM III (BFC)	REF <sup>a</sup> 100	2.52	–
	OS 4 100	2.34	1.00
	OS 4 95	2.03	0.87
	OS 4 85	1.63	0.69
	OS 4 75	1.45	0.62
	OS 4 65	1.08	0.46

<sup>a</sup>Uncoated reference specimen.

### 3.3 | Numerical simulation of chloride migration coefficients

To determine the chloride migration coefficients of the partially water-saturated concretes independent of the influence of the applied coating, the chloride migration tests carried out in the laboratory were reproduced in a FEM model with the help of the COMSOL Multiphysics® software in the first step.

For this purpose, the test specimens were first modeled with material properties that were uniform over the entire test specimen cross-section. On this basis, the migration coefficients of the protective surface coating were determined numerically by comparing the water-saturated coated and the water-saturated uncoated test specimens.<sup>[14]</sup>

In the next step, the test specimens were simulated in a two-layer system in which different migration coefficients were applied for the area of the surface protective coating and that of the concrete. The calculation of the migration coefficients of the partially water-saturated concretes was then carried out iteratively by adjusting the values for the desired migration coefficient until the penetration depths obtained in the two-layer system matched the results of the one-layer system (see Figure 7).

Table 2 shows the respective mean values of the simulated migration coefficients for the examined moisture contents and the reduction factors of the partially water-saturated concretes derived therefrom in comparison to the water-saturated reference concretes.

Figure 8 graphically shows the reduction factors for the migration coefficients as a function of relative humidity for the two concretes investigated.

In addition, the results of diffusion tests on partially water-saturated concretes by Climent et al.<sup>[21]</sup> were added to the diagram. To enable a comparison of the different test series, the results of Climent were also converted to a reduction factor in relation to the reference value of the water-saturated test specimens.

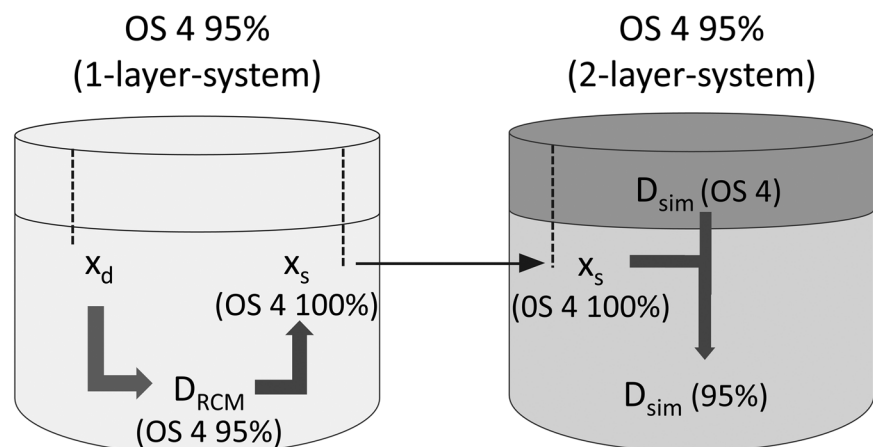
**TABLE 2** Numerically determined migration coefficients and reduction factors of the partially water-saturated concretes compared to the water-saturated reference concretes

Specimen	Conditioning (% RH)	$D_{sim}$ ( $10^{-12}$ m/s)	Reduction factor	
CEM I	REF <sup>a</sup>	100	18.04	–
	OS 4	100	18.23	1.00
	OS 4	95	14.75	0.82
	OS 4	85	10.17	0.56
	OS 4	75	6.62	0.37
	OS 4	65	3.32	0.18
CEM III	REF <sup>a</sup>	100	2.52	–
	OS 4	100	2.53	1.00
	OS 4	95	2.15	0.85
	OS 4	85	1.64	0.65
	OS 4	75	1.45	0.57
	OS 4	65	1.02	0.40

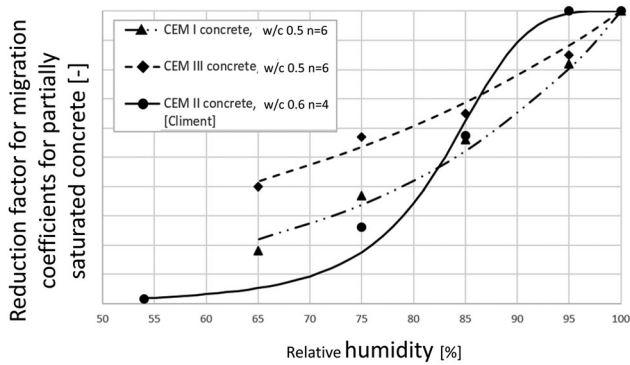
<sup>a</sup>Uncoated reference specimen.

A direct comparison of the numerically determined reduction factors for migration coefficients based on the RCM test series and the diffusion coefficients experimentally determined by Climent et al.<sup>[21]</sup> is only possible to a limited extent, as concretes with different types of binders and different water–cement ratios were investigated in the various test series, and these two parameters have a significant influence on the pore radius distribution in the concrete.

Besides, the reduction factors of both investigations in the humidity range between 65% and 85% are in a comparable size range. Significant differences can be seen in the 95% humidity range. Whereas Climent's investigations determined almost the same diffusion coefficient as the water-saturated reference sample, the investigations within the framework of the DFG project showed a reduction of the diffusion coefficient by an average of 18 (CEM I concrete) and 15% (CEM III concrete) in relation to the



**FIGURE 7** Procedure for the numerical calculation of the migration coefficients of partially water-saturated concretes



**FIGURE 8** Numerically determined reduction factors for migration coefficients at partial water saturation compared to the migration coefficients determined experimentally by Climent et al.<sup>[21]</sup>

water-saturated reference. The higher diffusion coefficients in the Climent test series can be attributed to the concentrated application of vaporous hydrochloric acid to the test specimens. The process leads to a change in the concrete structure in the near-surface area. Due to the concentrated impact, the chloride-binding capacity of the concrete is reduced locally, which leads to higher chloride values inside the component. Especially at high humidity contents, the hygroscopic effect of the chlorides leads to an absorption of additional water from the environment, which additionally favors a convective penetration of the chlorides.

### 3.4 | Model building

On the foundation of the laboratory tests carried out and the numerical simulations based on them, the following material-specific functions result for the concretes investigated to describe the reduction factors for migration coefficients of partially water-saturated concretes in comparison to the water-saturated reference concrete as a function of relative humidity.

CEM I 42.5 N, w/c 0.5:

$$\varphi_{RH} = 0.013e^{0.0434 \cdot RH}. \quad (15)$$

CEM III A 42.5 N, w/c 0.5:

$$\varphi_{RH} = 0.082e^{0.025 \cdot RH}, \quad (16)$$

where  $\varphi_{RH}$  is reduction factor of the migration coefficient of partially water-saturated concrete compared with water-saturated reference concrete, RH is relative humidity of the ambient air (%).

By extending Equation (14) with the material-specific reduction factor  $\varphi_{RH}$ , the chloride redistribution after “sealing a closed system” can be estimated for the

concretes investigated within the framework of this study project with the aid of Equation (17), taking into account the dehydration of concrete that can be expected as a tendency when applying the repair principle W-Cl as a function of the relative humidity of the ambient air.

$$c(x, t_b) = \frac{1}{L} \int_0^L f(z) dz + \sum_{n=0}^{\infty} \frac{2}{L} \int_0^L f(z) \cos\left(\frac{\pi \cdot n \cdot z}{L}\right) dz \cdot e^{-\left(\frac{n \cdot \pi}{L}\right)^2 \varphi_{RH} \cdot D_{app,C} \cdot t_b} \cdot \cos\left(\frac{\pi \cdot n \cdot z}{L}\right), \quad (17)$$

where  $\varphi_{RH}$  is reduction factor of the migration coefficient of partially water-saturated concrete compared with water-saturated reference concrete.

When using this approach, it should be noted that the concrete generally does not dehydrate until some time after the application of the coating, and the chloride redistribution is faster until then. In addition, it is to be expected that the degree of dehydration in the component will vary in different depth ranges, depending on the respective chloride concentration. For a precise characterization of the chloride redistribution in case of partial water saturation, a numerical calculation with consideration of depth-dependent diffusion coefficients is recommended.

## 4 | CONCLUSIONS

The focus of the investigations was the development of a model to describe the chloride redistribution after application of a system sealing surface protective coating. First, a mathematical model with a self-contained analytical solution was developed, with the help of which the chloride redistribution can be calculated, assuming complete water saturation of the concrete after application of a system sealing surface protective coating.

Then, the influence of the dehydration of the concrete expected as a result of the application of the repair principle W-Cl on the chloride redistribution in the sealed system was investigated. On the basis of the investigations carried out and the numerical calculations based on them, material-specific reduction functions were developed, with the aid of which the dependence of the chloride diffusion coefficient on the ambient humidity can be described.

Finally, the material-specific reduction functions were integrated into the developed analytical approach, which enables the calculation of chloride redistribution after system sealing as a function of moisture conditioning.

Recommendations for the practice with regard to the application limits of the repair principle W-Cl are dealt with in the following publication on the basis of the



developed analytical model in the context of parameter studies.

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