CHLORIDE TRANSPORT IN CONCRETE STRUCTURAL ELEMENTS AFTER REPAIR

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Abstract

This paper deals with the chloride transport in concrete elements after a repair measure in which the concrete cover was partially replaced with a repair material. Numerical calculations are used to establish criteria for the depth to which the concrete cover must be removed if the remaining layer of concrete is contaminated with chlorides. Compliance with these criteria is essential to prevent the residual chlorides causing depassivation of the reinforcing steel, apart from any effect of external chlorides by exposure after the repair measure. The results of ongoing laboratory investigations are presented. These demonstrate a favourable extraction of the chlorides present in the remaining concrete element by the repair layer. It is intended to use the results to develop a concept for evaluating the durability of concrete elements after repair with respect to chloride-induced corrosion of the reinforcing steel.

Keywords: Concrete, Chloride, Corrosion, Diffusion, Multilayer system, Repair measure, FEM, Service life design

1 Introduction

Chloride-induced corrosion is the decisive aspect governing the durability of structures in saline environments. Corrosion of the reinforcement is initiated when chloride ions penetrate into concrete and reach a critical concentration (threshold) at the surface of the rebar which disrupts the passive layer protecting the rebar. Such corrosion has consequences for the serviceability and loadbearing capacity of the structure. Cracking, spalling, loss of bond between rebars and concrete and a reduction in the rebar cross-section or even failure of the concrete element could occur.

A traditional and feasible repair measure is the application of cement-based repair mortars or concretes. Depending on the depth of chloride penetration and the chloride concentration in the structural element, the concrete cover is removed either partially or completely, as are deeper areas behind the reinforcement if necessary, and replaced with repair material. The objective of such repairs is to either maintain passivity or repassivate the reinforcing steel and enhance the resistance of the element to further chloride penetration.

It is currently not possible to plan and evaluate repair measures and assess the residual service life of the repaired structures reliably, as the mechanisms of chloride transport in multilayer concrete elements comprising existing concrete and an applied repair material have not been clarified. The mathematical description of this process is missing.

In the case of new structures (1-layer systems), time-dependent models, mainly based on Fick's 2nd law of diffusion, are used to describe chloride ingress into concrete, thus permitting the service life design of structures. For repaired structures, the transport model first has to be adapted to a multilayer model that considers both the layer of repair material and the remaining concrete layer. Where chloride ions are present in the remaining concrete layer, redistribution, i.e. transport into the repair layer as well as towards the inside of the structure, has to be considered.

When analysing and describing the chloride transport in concrete elements with regard to depassivation of rebars a distinction must be made between three cases according to the way in which the repair is carried out:

1) The concrete cover is removed entirely and replaced with a repair material. The remaining layer of concrete behind the reinforcement is not affected by chloride ions (1-layer system).

2) The concrete cover is only partially removed and replaced with a repair material. The remaining layer of concrete in the cover and behind the reinforcement is not affected by chloride ions (2-layer system without residual chlorides).

3) The concrete cover is only partially removed and replaced with a repair material. The remaining concrete layer contains (residual) chlorides. The same situation occurs when the contaminated concrete cover is left in place and topped with a layer of repair material (2-layer system with residual chlorides).

This paper presents mathematical approaches for calculating the time- and depth-dependent chloride concentration in concrete elements for the first two scenarios. For the third case, the problem of describing chloride transport mathematically owing to the redistribution of the residual chlorides in the element is addressed. Results of laboratory tests and numerical investigations using the Finite Element Method performed to analyse the redistribution of the residual chlorides are presented and discussed in order to answer the following two questions:

1) Are residual chlorides partially extracted by the new repair layer? Or will the available moisture in the new repair layer result in movement of the residual chlorides towards the interior of the element? (investigated by means of practical laboratory tests)

2) Under what boundary conditions will there be no risk of the existing chloride gradient causing depassivation of the reinforcing steel? To what depth should the chloride-contaminated concrete be removed? (investigated by means of numerical analyses)

2 Modelling the chloride transport in repaired concrete elements

As mentioned above, three different cases need to be considered if studying the chloride transport when repairs involving the replacement of sections of the concrete with a repair material are carried out:

2.1 Modelling the chloride transport in a 1-layer system (case no. 1)

The first and possibly the most common case arises when the concrete cover is removed entirely and replaced with a repair material (Fig. 1). The remaining layer of concrete behind the reinforcement is not affected by chloride ions. In this case, the chloride transport with respect to the chloride-induced corrosion of rebars is considered for a common 1-layer system consisting of the repair material in the same way as for new structural elements.

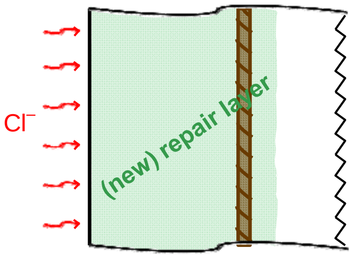


Fig. 1 Complete removal of cover and replacement with repair material (case no. 1)

Chloride transport in concrete was first modelled by *Collepardi et al.* in 1970. The model, known as Fick's second law of diffusion, is shown in equation (1) in its original form as a differential equation.

$$\frac{\partial C}{\partial t} = D \cdot \frac{\partial^2 C}{\partial x^2} \tag{1}$$

where D is the chloride diffusion coefficient of the concrete [m²/s] which is taken as constant, i.e. not dependent on time. An engineering model widely used to calculate the time- and depth-dependent chloride concentration in concrete was published in "*fib* Model Code for Service Life Design, *fib* Bulletin 34 (2006)" and "*fib* Model Code for Concrete Structures (2010)". In a somewhat simplified and modified form, it provides the solution to the above differential equation (equation (2)):

$$C(x,t) = C_0 + \left(C_{S,0} - C_0\right) \cdot erfc \frac{x}{2 \cdot \sqrt{k_e \cdot D_{app}(t) \cdot t}} \tag{2}$$

where:

C_0:	initial chloride content [wt.-%/c]
$C_{S,0}$:	chloride concentration on the surface of the element at the time of observation as a function of the available chloride source which is taken to be a constant action (surface chloride concentration) [wt.-%/c]
x:	depth with a corresponding content of chlorides $C(x, t)$ [m]
t:	time [s]
k_e:	environmental variable [–]
$D_{app}(t)$:	apparent chloride diffusion coefficient [m²/s]
$erfc$:	complementary (Gauss) error function (1-erf)

This diffusion-controlled assessment of chloride ingress is only a simplification since other transport mechanisms are involved in chloride ingress into in-situ concrete, including capillary absorption and permeation in particular. However, in structures with concrete cover depths exceeding thickness of 30 mm, diffusion becomes the most effective and important mechanism for the initiation of corrosion in concrete structures.

The chloride transport close to the surface may, however, deviate to a great extent from Fick's law of diffusion if elements are subject to cyclic chloride exposure such as in trafficked areas (treatment with de-icing agents in winter) and in tidal and splash zones of coastal structures. In such cases, modelling is performed with a substitute surface chloride concentration. The chloride concentrations in the convection zone are disregarded (for a conservative design) (*fib* 2006, Gehlen 2000).

Temperature affects the mobility of ions and hence the diffusion rate of chlorides. The transfer parameter k_e is introduced in order to take account of the impact of the external temperature on the chloride diffusion in concrete and can be calculated by using the Arrhenius equation for simplicity (*fib* 2006).

The apparent chloride diffusion coefficient $D_{app}(t)$, which represents the material resistance from t_0 to t as a constant, is subject to considerable scatter and tends to decrease with increasing exposure time. This implies that $D_{app}(t_2) < D_{app}(t_1)$ with $t_2 > t_1$. The apparent chloride diffusion coefficient is primarily affected by the type of binder and the exposure conditions. $D_{app}(t)$ is usually determined by means of an inverse analysis of measured chloride profiles from existing structures and / or laboratory diffusion tests. *Gehlen* introduced an alternative method of determining $D_{app}(t)$ for cases where a considerable quantity of field data is available for concretes similar to the design concrete (the concrete to be designed) (Gehlen 2000). In this method, the long and costly diffusion test (CEN/TS 12390-11:2010, NT Build 443 (1995)) is replaced by the simple Rapid Chloride Migration (RCM) test (NT Build 492 (1999), BAW 2012).

This paper does not include a detailed presentation and explanation of the model parameters. The model is described in detail in Gehlen 2000 and *fib* 2006. A statistically quantified database is available for this model, thus the model for describing chloride penetration presented in this paper is used to predict the chloride-induced depassivation of the reinforcement. The model is calibrated for the long term and under field conditions using data for existing structures that are up to 100 years old.

2.2 Modelling the chloride transport in a 2-layer system without residual chlorides (case no. 2)

The second case arises when the concrete cover is only partially removed and replaced with a repair material (Fig. 2). The remaining layer of concrete in the cover and behind the reinforcement is not affected by chloride ions. In this case, the concrete cover comprises two layers with different material characteristics: a new layer ("new") and the remaining layer ("remain"). The initiation period of corrosion depends on the chloride penetration behavior of the two layers.

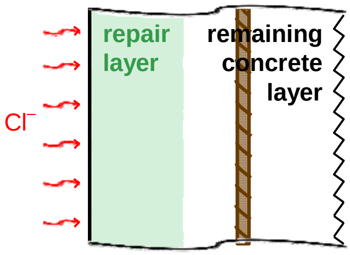


Fig. 2 Partial removal of cover and replacement with repair material (case no. 2)

The mathematical modelling of the penetration behaviour of chloride ions in such 2-layer systems can be performed as follows using the diffusion equations developed by Carslaw & Jaeger 1959 and Crank 1975 and by modifying the model for 1-layer systems (equation (2)):

$$C_{new}(x,t) = C_{S,0} \cdot \sum_{n=0}^{\infty} \gamma^n \cdot \left\{ erfc\frac{(2n+1)\cdot d_{c,new} + x}{2\sqrt{k_e \cdot D_{app,new}(t)\cdot t}} - \gamma \cdot erfc\frac{(2n+1)\cdot d_{c,new} - x}{2\sqrt{k_e \cdot D_{app,new}(t)\cdot t}} \right\} \tag{3}$$

$$C_{remain}(x,t) = \frac{2k \cdot C_{S,0}}{k+1} \cdot \sum_{n=0}^{\infty} \gamma^n \cdot erfc\frac{(2n+1)\cdot d_{c,new} + k\cdot x}{2\sqrt{k_e \cdot D_{app,new}(t)\cdot t}} \tag{4}$$

with:

$$k = \sqrt{\frac{D_{app,new}}{D_{app,remain}}} \tag{5}$$

$$\gamma = \frac{1-k}{1+k} \tag{6}$$

where $D_{app,new}(t)$ and $D_{app,remain}(t)$ are the apparent chloride diffusion coefficients of the repair material and the remaining concrete respectively; $d_{c,new}$ is the thickness of the repair layer. The chloride concentration in the layer of repair material $C_{new}(x, t)$ is described using equation (3) and that of the remaining layer of concrete $C_{remain}(x, t)$ using equation (4). The boundary conditions for the new layer are a constant surface chloride concentration ($C_{s,0}$ = const.) and an equilibrium concentration at the interface ($C_{new}(x=0, t) = C_{remain}(x=0, t)$).

Any interfacial resistance at the repair material / concrete layer interface is disregarded here. The interfacial resistance can be caused by the incoherence of the pore structure of the two materials (pore blocking) and by the high proportion of impermeable aggregates in both layers. In this case, the boundary condition of the equilibrium concentration at the interface is not satisfied in the above approach; the chloride transport is modelled using other, similar mathematical equations (Crank 1975).

2.3 Modelling the chloride transport in a 2-layer system with residual chlorides (case no. 3)

The third case arises when the concrete cover is only partially removed and replaced with repair material. The remaining layer of concrete contains (residual) chlorides (Fig. 3). The same situation occurs when the chloride-contaminated concrete cover is left in place and topped with a layer of repair material.

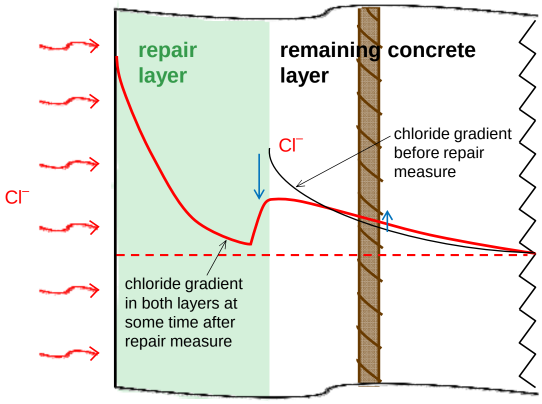


Fig. 3 Chloride ingress and redistribution in a repaired concrete element (2-layer system) with residual chlorides (case no. 3)

In this case, the result is also a 2-layer system except that, by contrast with case no. 2, the residual chlorides are redistributed in the new layer and within the structural element in addition to chloride ingress, see Fig. 3. The redistribution of the residual chlorides cannot be described mathematically by the error function solution of Fick's second law of diffusion as the required boundary condition of a constant concentration at the phase boundary, $\partial C_s/\partial t = 0$, no longer applies. The corresponding convolution integral, assuming that the apparent chloride diffusion coefficient D is the same for both layers and the residual chloride profile follows Fick's law of diffusion, is shown in equation (7). The integral does not provide a closed-form solution, i.e. it cannot be expressed as a finite number of known functions.

$$C(x,t) = \frac{1}{\sqrt{4\pi D \cdot t}} \int_x^{\infty} e^{-\frac{(x-y)^2}{4D\cdot t}} \cdot C_{s,0} \cdot erfc(\frac{y}{\sqrt{4D \cdot t}})\, dy \tag{7}$$

The interval x to ∞ indicates the boundaries of the remaining concrete layer; $C_{s,0}$ is the residual chloride content at the interface.

In this case, it is not possible to model the chloride transport in the element mathematically in a way that is generally valid. The diffusion-controlled chloride ingress and redistribution in a 2-layer system in the presence of residual chlorides will be investigated numerically in section 3 using the Finite Element Method.

A distinct mobilization of the residual chlorides, triggered by the moisture in the new repair layer, is expected to occur directly after application of the repair material. The residual chlorides may penetrate further into the original concrete layer owing to capillary suction or, conversely, be transported into the new layer (diffusion-controlled). The extent to which the chloride ions are transported into the new layer may vary, depending on the moisture content of the original concrete layer. This important issue is currently being investigated in ongoing laboratory investigations and is discussed in section 4.

3 Numerical investigations on chloride penetration in a 2-layer system

As explained in section 2.3, it is not possible to model the chloride transport in a repaired concrete element by means of mathematical functions if residual chlorides are present in the remaining concrete layer. However, it is possible to follow the transport of the chlorides with the Finite Difference or Finite Element Method with the aid of computer software.

The chloride ingress and redistribution in a 2-layer system was investigated using the

COMSOL Multiphysics® software. The numerical investigations aim to establish boundary conditions for the depth of concrete removal and the remaining chloride gradient below which there is no risk of the residual chlorides causing depassivation of the reinforcing steel. The chloride penetration was considered to be by diffusion only and is described using Fick's law. The mechanisms are modelled in the software by means of differential equations and solved using the Finite Element Method (FEM).

The following two boundary conditions were established on the basis of the results of numerous (numerical) cases. The boundary conditions must be satisfied in order to prevent depassivation of the reinforcing steel (which occurs when the critical chloride content C_{crit}, at which corrosion is initiated, is reached at the surface of the reinforcing steel) by redistribution of the residual chlorides in the remaining concrete layer:

1) The maximum residual chloride content must not exceed 2.0 % by weight of binder.

2) There should be a distance of at least 10 mm between the surface of the reinforcing steel and the depth at which the critical chloride content C_{crit}, at which corrosion is initiated, is reached.

This means that the concrete layer contaminated with chlorides must be removed to a depth at which both of the boundary conditions stated above are satisfied. However, this procedure is conditional upon the residual chloride profile corresponding to Fick's law of diffusion.

The results of the selected theoretical cases shown in Fig. 4 to Fig. 12 illustrate the diffusion-controlled redistribution and ingress of chlorides in repaired concrete elements and demonstrate the plausibility of the conditions defined above.

Fig. 4 shows the chloride redistribution in a concrete element after the 55 mm thick concrete cover was partially removed (25 mm) and subsequently sealed. The residual chloride profile (initial Cl, cf. Fig. 4) satisfies both boundary conditions and has the maximum permitted limiting values. The chosen concrete is a material with a very low resistance to chloride ingress (e.g. made with Portland cement with a w/c-ratio of 0.60). The diffusion-controlled redistribution of the residual chlorides 1, 5, 10, 20 and 50 years after the concrete had been repaired is shown. There is a distinct decrease in the chloride content in the near-surface zone which is very pronounced at the beginning (t = 1a) and becomes less marked over time. At the level of the uppermost surface of the reinforcing steel the chloride content first increases (t = 1 and 5a) but decreases again over time and always remains below the critical chloride content C_{crit} of 0.50 wt.-%/c at which corrosion is initiated. Thus it can be assumed that there is no risk of the residual chlorides causing depassivation of the reinforcing steel. The critical chloride content for the initiation of corrosion C_{crit} is taken to be 0.5 wt.-%/c on average in many standards and directives, such as RiLi SIB (2001) and ÖVBB-Richtlinie (2003).

Section 2.1 dealt with the increase in the apparent chloride diffusion coefficient of the concrete over time $D_{app}(t)$ and thus the enhancement of the resistance to chloride ingress. The calculations considered, conservatively, the apparent chloride diffusion coefficient of the remaining concrete layer from the time at which the repair was carried out. The age of the concrete element prior to repair was not taken into account.

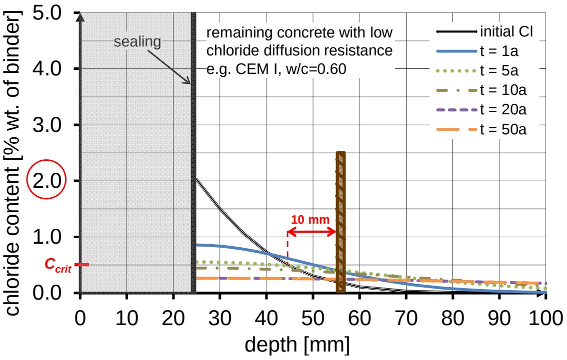


Fig. 4 Redistribution of residual chlorides in a concrete with low chloride diffusion resistance after partial removal (25 mm) of cover and sealing. The residual chloride profile exhibits a maximum of 2.0 wt.-%/c and falls below C_{crit} at 10 mm from the rebar surface.

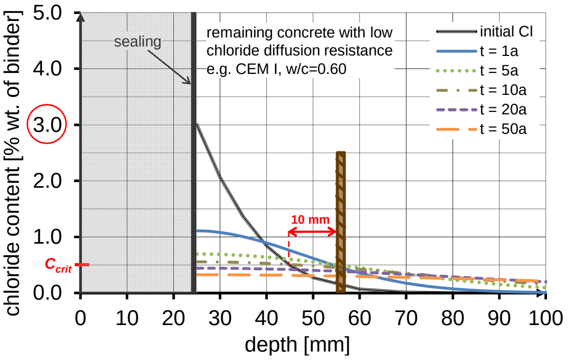


Fig. 5 Redistribution of residual chlorides; same case as in Fig. 4 but the residual chloride profile exhibits a higher maximum of 3.0 wt.-%/c; impact of maximum chloride content in remaining concrete on depassivation of rebar.

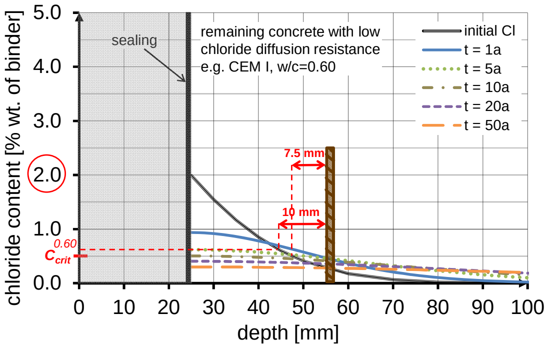


Fig. 6 Redistribution of residual chlorides; same case as in Fig. 4 but the depth with C_{crit} is only 7.5 mm (less than 10 mm) from the rebar surface; impact of the distance of the depth with C_{crit} to rebar surface.

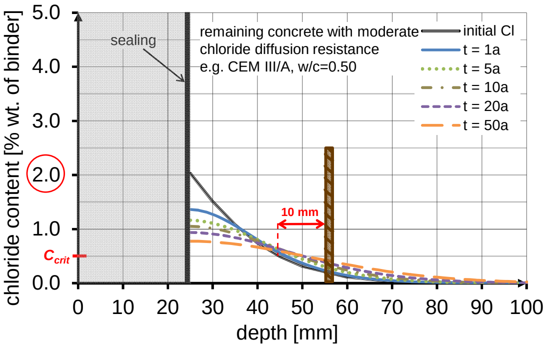


Fig. 7 Redistribution of residual chlorides; same case as in Fig. 4 but remaining concrete has a higher resistance against chloride diffusion; impact of the diffusivity of remaining concrete.

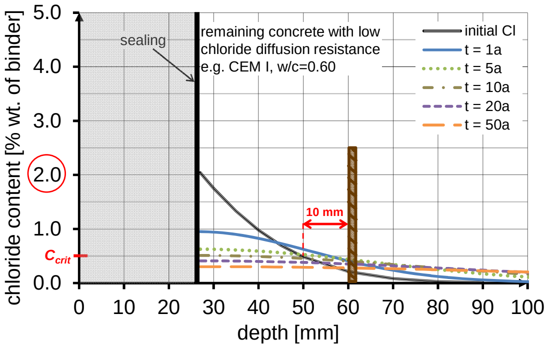


Fig. 8 Redistribution of residual chlorides; same case as in Fig. 4 but with a different concrete cover (60 mm instead of 55 mm) and thickness of repair layer (27 mm instead of 25 mm); impact of variation in cover dimension.

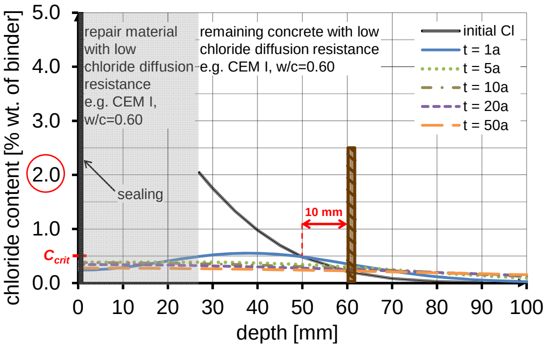


Fig. 9 Redistribution of residual chlorides; same case as in Fig. 8 but the removed cover is replaced by a repair material; impact of chloride extraction ("back-diffusion") by the repair layer.

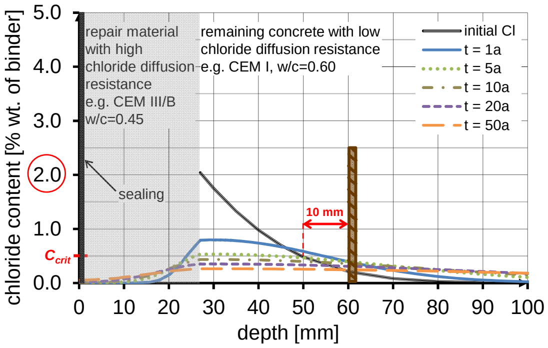


Fig. 10 Redistribution of residual chlorides; same case as in Fig. 9 but the repair material exhibits a much higher resistance to chloride diffusion; impact of diffusivity of repair material.

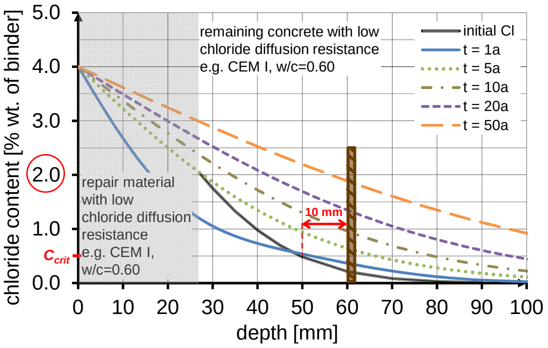


Fig. 11 Ingress and redistribution of chlorides; same case as in Fig. 9 but external chlorides ingress through the repair layer.

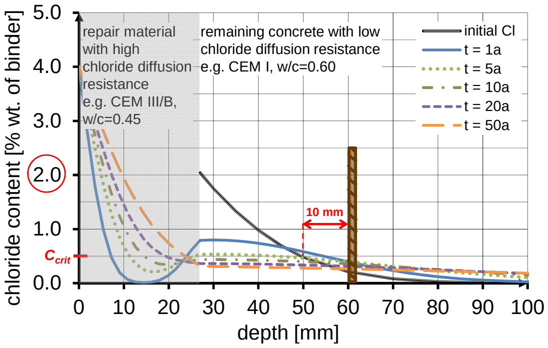


Fig. 12 Ingress and redistribution of chlorides; same case as in Fig. 9 but the repair material exhibits a much higher resistance to chloride diffusion (same case as in Fig. 10 but with external chlorides); impact of diffusivity of repair material.

In a second case (cf. Fig. 5), the maximum chloride content was increased to 3.0 wt.-%/c by way of departure from the first boundary condition (the concrete and concrete cover being the same as in the first case). It can be seen in Fig. 5 that the critical chloride content at the surface of the reinforcing steel was reached at t = 1 and 5 years so that the risk of the residual chlorides causing depassivation of the reinforcing steel cannot be ruled out.

Fig. 6 illustrates the theoretical case in which the residual chloride profile, deviating from the second boundary condition, exhibits the critical chloride content C_{crit} at a distance of only 7.5 mm from the surface of the reinforcing steel (instead of 10 mm). The chloride content at a distance of 10 mm from surface of the reinforcing steel is 0.60 wt.-%/c. Similar to the previous case in Fig. 5, the chloride profiles at t = 1 and 5 years also exhibit chloride contents equal to or slightly higher than C_{crit} at the surface of the reinforcing steel.

In Fig. 7, a concrete with a higher resistance to chloride ingress was considered (e.g. with CEM III/A with a w/c-ratio of 0.50) and compared with the first case (Fig. 4). The stated boundary conditions are also shown to be valid in this case. The chloride redistribution is considerably slower. By contrast with the previous cases, in which the chloride content at the surface of the reinforcing steel rapidly increased initially (t = 1 and 5a) and then decreased (t = 10, 20 and 50a), the chloride content at the surface of the reinforcing steel rises continuously from t = 1a to t = 50, but remains below the critical content C_{crit}.

In the cases considered so far, the nominal concrete cover was taken as 55 mm in accordance with the provisions of the European Standard in conjunction with the German national annex DIN EN 1992-1-1/NA:2013 for exposure classes XD and XS. In Germany, the guideline ZTV-W LB 215:2012 also applies to structures on waterways and in coastal areas and specifies a higher nominal concrete cover of 60 mm for exposure classes XD and XS. It is for this reason and for the purposes of investigating the validity of the defined boundary conditions for other concrete cover dimensions that the first case in Fig. 4 was considered with a concrete cover of 60 mm (cf. Fig. 8). A residual chloride profile corresponding to the error function solution of Fick's 2nd law of diffusion and with the limiting values of both boundary conditions resulted in a depth of 27 mm for removal of the concrete. As can be seen in Fig. 8, the chloride content at the surface of the reinforcing steel always remains below C_{crit}.

Fig. 9 illustrates the case in which the removed concrete cover was replaced with a repair material as in the previous case (Fig. 8) (instead of being sealed). The thickness of the concrete cover is therefore unchanged, at 60 mm. The repair material used was the same porous material with a very low chloride diffusion resistance as that of the remaining element (Portland cement concrete with a w/c-ratio of 0.60). The surface of the element was then sealed to prevent the ingress of external chlorides. In this case, the residual chlorides will diffuse into the new layer as well as being redistributed in the remaining concrete layer. The extraction of the residual chlorides by the new layer results in a lower redistribution into the remaining layer and thus in a lower chloride content at the surface of the reinforcing steel at each of the times considered than was the case in Fig. 8 in which the element was only sealed after the concrete cover had been removed.

Furthermore, a case was investigated in which the repair material is a dense concrete with a high resistance to chloride ingress (e.g. CEM III/B concrete with a w/c-ratio of 0.45) (cf. Fig. 10). In contrast to the previous case in which a porous repair material was used, residual chlorides are extracted by the new layer to a far lesser extent. A "diffusion-open" repair material is thus more favourable as regards the extraction of residual chlorides.

In practice, the surface of the structural element is not usually sealed after application of the repair material so that external chlorides can be expected to penetrate into the concrete. Fig. 11 and Fig. 12 show the last two cases described above (Fig. 9 and Fig. 10) when, in addition to the residual chlorides present in the concrete, external chlorides penetrate into the element. The figures clearly show that, as expected, a diffusion-tight repair material significantly increases the resistance of the element to chloride ingress, by contrast with the diffusion-open material. A comparison of Fig. 10 and Fig. 12 clearly shows that, up to t = 20 a, the external chlorides have not yet reached the remaining concrete layer. A slight difference between the chloride profiles in the vicinity of the remaining concrete layer is, in both cases, only detectable at t = 50 a, indicating that external chlorides have penetrated into the repair layer.

In the cases considered, the validity of the boundary conditions described above with regard to preventing the risk of residual chlorides causing depassivation of the reinforcing steel was examined and verified. When doing so, unfavourable cases of relevance in practice were considered and the possibility of the residual chlorides being extracted by capillary suction and washed out of the freshly applied repair layer was disregarded to be on the safe side (cf. section 4). Similarly, the favourable effect of the age of the element when the repair was carried out on the resistance of the remaining concrete to chloride penetration was not taken into account either. Thus the defined boundary conditions can be considered as general, conservative criteria for repairing concrete elements.

The following section deals with ongoing laboratory investigations into the chloride transport in a 2-layer system, focusing in particular on the extraction of the residual chlorides by the new repair layer.

4 Laboratory investigations on chloride transport in a 2-layer system

Laboratory investigations are currently being conducted to observe chloride transport mechanisms in a 2-layer system. Composite specimens comprising a concrete layer with chloride gradients and a layer of repair material (Fig. 13) were prepared for the investigations. The ingress, redistribution and extraction mechanisms for chloride ions in the layer of repair material and the layer of concrete are being studied in long-term laboratory storage (diffusion) tests. The storage tests with the different types of specimen and the storage conditions are summarized in Table 1. Three different types of concrete (ordinary Portland cement (320 kg/m³) with different w/c-ratios: 0.55, 0.60 and 0.65, aggregate: gravel with grading AB 8) and a single repair material (PCC: Polymer modified Cement Concrete, max. grain size 2 mm) are being investigated.

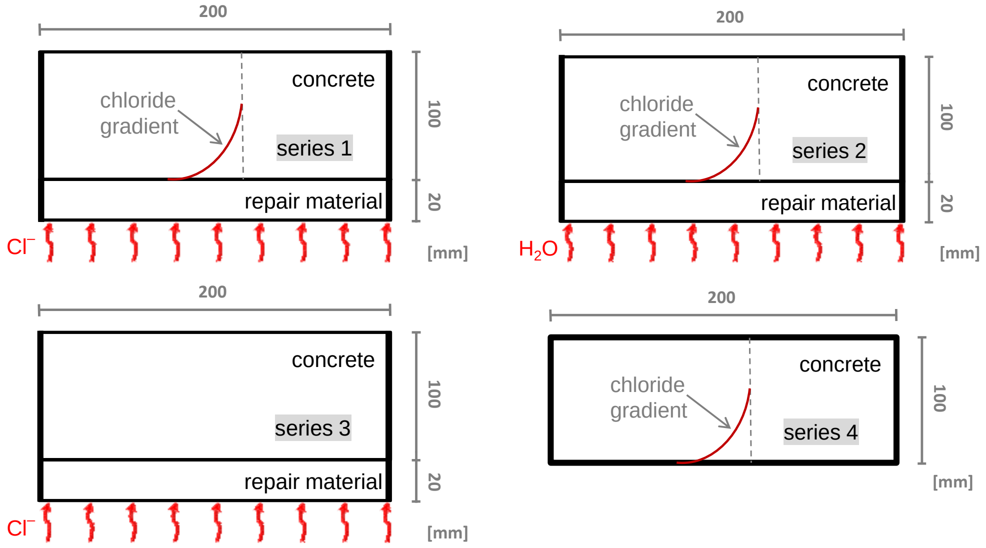


Fig. 13 Sketch of the specimens used for the laboratory storage tests (width: 200 mm)

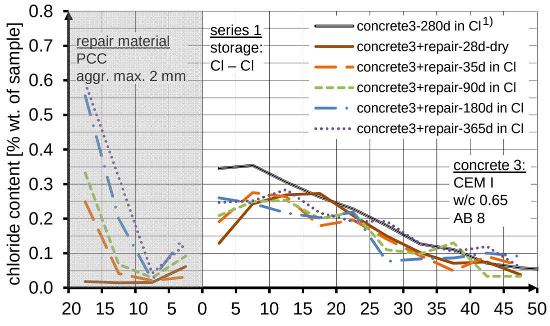
Table 1
Storage (diffusion) tests to investigate the chloride transport in a 2-layer system

test series	specimen	pretreatment – storage	studying mechanism
1	composite specimen with chloride gradients in concrete	Cl – Cl	D, E, R
2	composite specimen with chloride gradients in concrete	Cl – water	E, R
3	composite specimen	20 °C/65 % RH – Cl	D
4	concrete specimen with chloride gradients	Cl – 20 °C/65 % RH	R

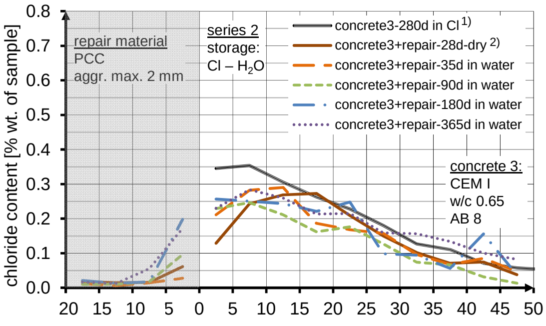
D: Diffusion (ingress) of external chloride ions into the repair layer and further into the concrete layer
E: Extraction (“Back-diffusion”) of residual chloride ions from the concrete into the repair layer
R: Redistribution of residual chloride ions in the concrete layer

The concrete specimens were first stored in a 3% NaCl solution for around 280 days (over 9 months) (one-sided exposure). The chloride gradients in the specimens were determined and the specimens were then topped with a repair mortar (20 mm), series 1 to 3. The surfaces of the concrete test specimens were sand-blasted immediately prior to application of the mortar layer in order to achieve a better bond between the two layers, material being removed to a mean depth of around 1 mm. The concrete test specimens were taken out of the 3% NaCl solution around one and a half days before application of the repair mortar and stored in laboratory conditions (20 °C/65 % RH). The composite specimens were then stored in the laboratory at 20 °C / 65 % RH for 28 days. At this point, the change in the chloride gradient was investigated (chloride profiles) before the specimens were stored as shown in Table 1. In test series 1, the composite specimens were stored in a 3 % NaCl solution in order to investigate each of the processes occurring during chloride transport in a 2-layer system (D, E, R, cf. Table 1). In test series 2, the composite specimens were stored in water in order to observe the redistribution and extraction through the repair layer. In series 3, composite specimens without chlorides in the concrete layer were stored in a 3% NaCl solution in order to investigate the chloride diffusion without the presence of chloride gradients in the concrete layer. In the last test series (4), the concrete specimens were sealed on all sides with epoxy resin after being stored in the chloride solution for 280 days and subsequently stored in dry conditions in the laboratory at 20 °C / 65 % RH in order to observe the internal redistribution of the chlorides.

The results obtained hitherto for the concrete with the w/c-ratio of 0.65 will now be considered by way of an example. The concrete concerned exhibits the most rapid and extensive chloride movement as it is more porous and diffusion-open than those concretes with lower water/binder ratios. Figures 14, 15 and 16 show the chloride profiles as mean values of the chloride contents determined for two specimens (per test series) at different times up to one year after storage began. Test series 4 was not considered here as the results obtained so far did not seem realistic and their plausibility has yet to be checked. In order to establish the chloride profiles, slices were cut with a spacing of 5 mm from the full depth of two specimens of each concrete and subsequently ground. The chloride contents were stated in % by weight of the sample and not, as usual, by weight of the binder (or cement) as the binder content of the repair material used (PCC) was unknown. The compositions of repair materials are not generally disclosed by the manufacturers.



[1] obtained on three additional specimens



[1] obtained on three additional specimens

[2] obtained on both specimens in series 1

Fig. 14 Chloride profiles of test series 1 (storage Cl – Cl, cf. Table 1); ingress of external chlorides and extraction and redistribution of initial chlorides.

Fig. 15 Chloride profiles of test series 2 (storage Cl – H_2O, cf. Table 1); extraction and redistribution of initial chlorides.

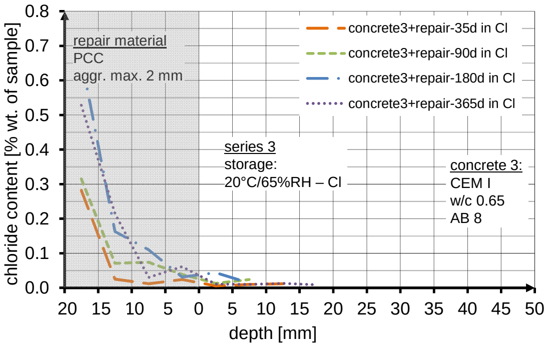


Fig. 16 Chloride profiles of test series 3 (storage 20 °C/65 % RH – Cl, cf. Table 1); ingress of external chlorides.

The chloride profiles in Figures 14 and 15 (series 1 and 2) demonstrate that the extraction of the "internal" chlorides in the concrete layer by the repair layer was continuous over the period of time considered. The chloride content at the first measuring level in repair layer increases almost constantly over time and the penetration depth increases. A pronounced reduction in the chloride content in the concrete layer in the zone closest to the interface can be seen in the first profile (after application of the repair layer and before storage began). The quantity shown is greater than the quantity extracted from the repair layer. The difference can partly be explained by the loss of material caused by the surface of the concrete element being sand-blasted prior to application of the repair material. The chloride content in this zone increases again slightly during the storage period. It is not yet possible to identify a pronounced redistribution of the chlorides in the concrete layer in the period of time under consideration.

It should be noted that the chloride profile prior to application of the repair layer is the mean value of the chloride contents measured on three additional specimens. The chloride profile after application of the repair layer and prior to the beginning of storage was determined by measuring the chloride content of two specimens of series 1. As neither the concrete nor the specimens are homogenous, the chloride profiles stated here may deviate slightly from the actual values. The chloride profiles are used here to make qualitative statements on the chloride transport in repaired elements.

The chloride profiles for series 3 in Fig. 16 show a continuous increase in the chloride content and the depth to which external chlorides penetrate into the repair layer. Although the chloride front has reached the interface with the concrete, a significant quantity of external chlorides has not yet penetrated into the concrete. The repair material used (PCC) was shown to be a very diffusion-tight material during further investigations of the chloride penetration resistance of concrete and repair materials. The values determined (chloride migration coefficient D_{RCM}, apparent chloride diffusion coefficient D_{app}, ageing exponent α) are in the same range as those of a dense CEM III/B concrete (repair material PCC I in *Rahimi* et al. (2014.09)).

The possible transport of the chlorides into the remaining concrete layer or into the new layer after application of the repair layer has already been discussed in section 2.3. The effects – capillary suction, diffusion and "washing out" – can promote transport of the chlorides in either direction. The moisture content of the new mortar layer was considerably higher than that of the remaining concrete layer. The distinct moisture gradient initially seems to indicate that water is being transported from the mortar layer into the concrete layer by capillary suction. This may promote transport of the chlorides from the surface of the test specimen into the inside of the specimen. However, the results of the laboratory tests indicate clearly that, as described above, chlorides are being extracted by the repair layer, presumably by diffusion. This diffusion-controlled transport of chloride ions into the new layer may be caused by the relatively high moisture content of the concrete specimens prior to application of the repair mortar. The diffusion resistance of the freshly applied repair material is considerably lower than that of the concrete, resulting in diffusion of the chlorides into the repair layer.

Studies by *Martin* (1975) of repaired concrete beams contaminated by chlorides have also shown that there is a substantial transport of residual chlorides into the new repair layer. In that case the beams exhibit very low moisture content prior to application of the repair material. The chloride profiles 2, 3 and 6 years after application of the repair layer also indicated a redistribution of the chlorides in the concrete of the beams (Martin 1975).

The results obtained hitherto for the other two concretes under investigation (with w/c = 0.55 and 0.60) show that the chloride profiles are similar. A pronounced extraction of the chlorides by the repair layer can also be seen for these series.

Further measurements of the chloride contents of the specimens are scheduled to be performed 1.5 and 2 years after the beginning of storage.

5 Conclusions and practical implications

This paper has dealt with the chloride transport in a concrete element which was repaired by partially replacing the concrete cover with a repair material. Three cases have been examined with a view to modelling the chloride transport to enable the chloride-induced corrosion of the reinforcing steel to be estimated. They differ with regard to the depth to which the concrete cover was removed and the chloride contamination of the remaining concrete layer.

In cases in which the concrete cover is replaced entirely by a repair material, the chloride transport model which already exists for new structures (1-layer system) (*fib* 2006, *fib* 2010) may be used. The chloride transport can also be modelled mathematically if the concrete cover is partially replaced (2-layer system) and the remaining concrete of the element does not contain any chlorides. However, it is not possible to model the redistribution of the chlorides mathematically using a finite number of known functions if the remaining concrete in the element is contaminated with chlorides.

The last case referred to above was investigated with the aid of numerical calculations and practical laboratory tests. The following general boundary conditions were established by means of numerical calculations performed with the Finite Element Method. These conditions must be satisfied if depassivation of the reinforcing steel as a result of the redistribution of the residual chlorides in the remaining concrete layer is to be prevented (without any effect of external chlorides):

1) The maximum residual chloride content must not exceed 2.0 % by weight of binder.
2) There should be a distance of at least 10 mm between the surface of the reinforcing steel and the depth at which the critical chloride content C_{crit}, at which corrosion is initiated, is reached.

Only the diffusion-controlled chloride transport has been considered in the FEM analyses. The criteria established were conservative as the following two aspects were disregarded. First, the favourable effect of the age of the concrete element when the repair measure was carried out on the resistance of the remaining concrete to chloride ingress was not taken into account. Second, the positive effect of the extraction of the residual chlorides from the new, fresh repair layer by capillary suction and washing out was not considered either. The extraction of the residual chlorides from the repair layer was verified in the practical laboratory tests.

The performance-based assessment of the durability of concrete structures is becoming more and more important. A mathematical model which enables the transport and/or deterioration mechanisms to be simulated with a sufficient degree of accuracy is a fundamental element of such a performance concept. A fully probabilistic performance concept for the durability of uncracked concrete elements has been developed for new structures with respect to chloride-induced depassivation of the reinforcing steel. The concept is now being applied internationally in design practice (*fib* 2006, *fib* 2010). The mathematical model in this concept was briefly described in section 2.1.

The chloride transport mechanisms in such multilayer systems must be demonstrated before such performance concepts can also be developed for assessing the durability of the resistance of concrete elements to chloride-induced corrosion of the reinforcing steel after the concrete has been repaired. The presence of residual chlorides in the remaining concrete layer means that it is not possible to establish a generally valid mathematical model for chloride transport. Nevertheless, an approach for an approximate calculation of the service life of repaired concrete elements was described in *Rahimi et al.* (2014.01). However, the paper only considered the residual chloride content at the surface of the reinforcing steel and any possible increase in the chloride content at the surface of the reinforcing steel owing to redistribution of the residual chlorides (in addition to ingression of external chlorides through both repaired and remained layer) was disregarded. The findings on the redistribution of chlorides described in this paper enable boundary conditions and applications for this approach to be defined. The final work on establishing a concept for the service life design of concrete structures being repaired is currently in progress.

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