Cement & Concrete Composites 34 (2012) 763–770

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

A fuzzy-probabilistic durability concept for strain-hardening cement-based composites (SHCC) exposed to chlorides: Part 2 – Application example

F. Altmann [a], J.-U. Sickert [b], V. Mechtcherine [a,*], M. Kaliske [b]

[a] Institute of Construction Materials, Technische Universität Dresden, Germany
[b] Institute for Structural Analysis, Technische Universität Dresden, Germany

ARTICLE INFO

Article history:
Available online 3 March 2012

Keywords:
SHCC
Durability
Service life
Chloride
Fuzziness
Fuzzy failure probability

ABSTRACT

In Part 1 of this treatise, a fuzzy-probabilistic approach for assessing the durability of SHCC exposed to chlorides is introduced. This approach may be considered as a framework for durability concepts for novel types of cementitious materials and different forms of environmental action. In this second part an application of this concept to crack-free SHCC exposed to a North Sea marine environment is presented. Special emphasis has been given to the transparent and reproducible quantification of input variables based on limited experimental investigations, literature review, and expert assessment. Based on these input variables, the buildup of chlorides at the depth of the steel bar reinforcement and development of the probability of corrosion initiation of the steel reinforcement over time were computed. It was found that the non-stochastic uncertainty due to information deficit is still significant. This currently precludes the concept from being used as a practical design tool. However, with the help of sensitivity analyses it was possible to identify the most influential input variables. It could be shown that with a reduction of this uncertainty, long service lives for SHCC members may be correctly demonstrated. This identification furthermore allows a targeting of future research efforts to reduce uncertainty in the most economical way.

1. Introduction

In Part 1 of this work strain-hardening cement-based composites (SHCC) are introduced, which are characterised by their pseudo strain-hardening tensile behaviour, resulting in ultimate strains of up to and beyond 3%. This ductile behaviour results from progressive multiple cracking achieved by the optimised crack-bridging action of short, thin, well distributed polymeric fibres [1].

To utilise the promising durability properties of this material fully, a performance-based durability concept is required. Based on the DuraCrete approach [2] and using fuzzy probability theory to deal with the lack of available information typical for any new material, such a concept was developed for chloride-induced corrosion.

Structural SHCC members will typically contain steel bar reinforcement [3,4]. The limit state for chloride-induced corrosion of this reinforcement can be written as

$$\tilde{g}(x = c, t) = C_{crit} - \tilde{C}(x = c, t) \tag{1}$$

with the variables as per Table 1. The tildes indicate fuzzy or fuzzy-stochastic uncertainty modelling. The time-dependent chloride concentration at the depth of the steel reinforcement is given by:

$$\tilde{C}(x = c, t) = C_0 + \left(\tilde{C}_{S,\Delta x} - C_0\right) erfc\left(\frac{c - \Delta x}{2\sqrt{\tilde{D}_a(t) \cdot t}}\right) \tag{2}$$

with the apparent diffusion coefficient

$$\tilde{D}_a = \tilde{T}_{cf}\tilde{D}_{ex,0,cf} + \tilde{T}_{cr}\tilde{D}_{ex,0,cr} \tag{3}$$

with

$$\tilde{T}_{cf} = \tilde{k}_e\tilde{k}_t\tilde{k}_c\frac{1}{1 - \tilde{n}_{cf}}\left[\left(1 + \frac{t'_{ex}}{t}\right)^{1-\tilde{n}_{cf}} - \left(\frac{t'_{ex}}{t}\right)^{1-\tilde{n}_{cf}}\right]\left(\frac{t'_0}{t}\right)^{\tilde{n}_{cf}} \tag{4}$$

and

$$\tilde{T}_{cr} = \tilde{k}_e\tilde{k}_{t,cr}\tilde{k}_{cr}\frac{1}{1 - \tilde{n}_{cr}}\left[\left(1 + \frac{t'_{ex}}{t}\right)^{1-\tilde{n}_{cr}} - \left(\frac{t'_{ex}}{t}\right)^{1-\tilde{n}_{cr}}\right]\left(\frac{t'_0}{t}\right)^{\tilde{n}_{cr}}. \tag{5}$$

The temperature influence is considered via the factor

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right). \tag{6}$$

Here in the second part of the paper, the fuzzy-probabilistic durability concept developed in Part 1 is used to determine the time-dependent probability of failure of a crack-free SHCC member

* Corresponding author.
E-mail address: mechtcherine@tu-dresden.de (V. Mechtcherine).

0958-9465/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2012.02.015

Table 1
Definition of variables and functions.

$g(c, t)$	Limit state function for the end of the initiation period of chloride-induced steel reinforcement corrosion; for $g(c, t) < 0$ steel corrosion may occur
C_{crit}	Critical chloride concentration (% by mass of binder)
$C(x, t)$	Chloride concentration at depth x and time t
C_0	Initial chloride content (% by mass of binder)
$C_{S,\Delta x}$	Chloride content at depth Δx (% by mass of binder)
x	Depth from surface (mm)
c	Concrete cover (mm)
Δx	Convection zone (mm)
$D_a(t)$	Apparent diffusion coefficient (10^{-12} m^2/s)
$D_{ex,0,cf}$	Diffusion coefficient of crack-free SHCC under laboratory conditions at time t'_0 (10^{-12} m^2/s)
$D_{ex,0,cr}$	Contribution of cracks to the diffusion coefficient of cracked SHCC under laboratory conditions at the time t'_0 (10^{-12} m^2/s)
erfc	Complementary error function
k_e	Temperature factor (–)
k_t	Transfer (regression) factor (–)
k_c	Curing factor
k_{cr}	Crack intensity factor (–)
t'_0	Reference time (years)
t'_{ex}	Concrete age at first exposure (years)
t	Duration of exposure (concrete age – t'_{ex})
n_{cf}	Age factor for crack-free material
n_{cr}	Age factor for crack contribution to diffusion

exposed to a North Sea marine environment. The analyses were performed using the software WinFuz, developed at the Institute for Structural Analysis, Technische Universität Dresden.

The purpose of this example is to show how the concept can be applied to real structural members subject to field exposure conditions, to demonstrate its capabilities and limitations, and to identify areas requiring further research.

The concept requires two models, one for the deterioration process (here: chloride ingress), and the other for the uncertainty associated with the deterioration model and its input variables. Compared to the concept developed in the DuraCrete project and its derivatives, both models in the concept discussed in this treatise are more complex. This is due to the fact that the deterioration model must consider the influence of cracks, and because comparatively little information is available about chloride ingress into SHCC and the quantitative influence of cracks.

The changes to the uncertainty model are more profound. They increase the complexity of the concept more than the changes to the deterioration model, and they are more difficult to understand. To give sufficient room to the discussion of the consequences of the fuzzy-probabilistic uncertainty model, it is helpful to consider an example in which only the uncertainty but not the deterioration model has been changed. Hence, a crack-free member will be investigated, and special emphasis is given to a transparent and reproducible quantification of input variables based on the available information and knowledge.

2. R/SHCC member exposed to seawater

2.1. Material details and exposure conditions

In Japan, SHCC has been successfully used for the waterproofing of dams and other water retaining structures such as water channels [5]. This experience makes the material interesting for similar applications in marine environments, where steel corrosion due to chloride ingress is a critical deterioration mechanism.

It is assumed that the member in question contains steel rebars with a nominal cover depth of $c = 50$ mm, that it is crack-free and submerged in the North Sea with a mean water temperature of T_{real} 10 °C, a coefficient of variation of $\mathrm{CoV}_{Treal} = 0.02$ [6] and a salinity of 20 g/l [7]. The SHCC used in this example is given in Table 2. Its mechanical performance is described in detail in [1].

Crack-free conditions were chosen deliberately despite SHCC components' typically exhibiting cracks in actual application under service loads. This limitation of input variables allows a detailed description of their quantification. An example of cracked SHCC, focussing only on the determination of the contribution of the bulk material and the cracks to the diffusion coefficient can be found in [8]. Here, most space is given to the age factor $\tilde{n}_{cf}$, which is of critical importance to the expected failure probability.

2.2. Chloride concentration $\tilde{C}_{S,\Delta x}$

Under submersion, it is $\Delta x = 0$ mm, and the chloride concentration $\tilde{C}_{S,\Delta x}$ becomes the surface chloride concentration. It is assumed constant in Eq. (2) and depends not only on the salinity of the seawater but also on the binding capacity of the SHCC. $\tilde{C}_{S,\Delta x}$ can be determined based on the mixture composition, the binding capacity of the matrix, and the seawater salinity according to the following equation [9]:

$$C_{S,\Delta x} = C_{bound} + V_{pore} \cdot c_{Cl} \tag{7}$$

with c_{Cl} (g/l) the chloride concentration in the solution and V_{pore} (–) the pore volume fraction. The concentration of bound chlorides C_{bound} (kg/m^3) is calculated by determining the hardened cement paste fraction of SHCC and multiplying it by a binding isotherm. According to [9], the Freundlich isotherm

$$C_{bound} = \left(\frac{(1 + w_n^0)f_c\alpha_h}{1 + w_n^0 f_c\alpha_h}\right) \cdot \left(f_b c^{\beta}\right) \tag{8}$$

provides the best fit for concrete submerged in seawater. In Eq. (8), it is $w_n^0 = 0.25$, the weight of chemically bound water for each unit weight of hydraulically active binder and full hydration according to Powers, $f_c = w_{binder}/(w_{binder} + w_{aggregates})$, the fraction of binder relative to the solids in the composition and α_h, the degree of hydration. The parameters f_b and β of the Freundlich isotherm are

Table 2
SHCC composition.

	(kg/m^3)
Portland cement	321
Fly ash (FA)	749
Fine sand	535
Water	335
Superplasticiser	16.6
Viscosity agent	3.2
PVA-fibres (l = 12 mm)	29.3

tabulated in [9] for Portland and blended cements. For a blended cement with 30% fly ash, it is $f_b = 5.77$ and $\beta = 0.29$.

With a hydraulically active binder content of $w_{binder} = w_{cement} + 0.4 \cdot w_{fly\ ash} \leqslant 1.33\ w_{cement}$ following [10] and the mixture composition according to Table 2, the surface chloride concentration can be calculated. For fully hydrated binder, a conservative assumption, it is $C_{S,\Delta x} = 2.91\%$ by mass of binder.

It must be noted that this binding isotherm is an empirical function with no clear physical and chemical meaning for the individual parameters, which were quantified based on a limited number of observations. The associated uncertainty is not separately quantified but considered through conservative assumptions regarding the distribution of $\tilde{C}_{S,\Delta x}$.

In probabilistic concepts, the distribution type and the standard deviation of $\tilde{C}_{S,\Delta x}$ are even less well-established and, often, a conservative assumption is made for the coefficient of variation due to a lack of available information [7]. In the concept presented here, fuzzy-probability theory is used to avoid having to estimate certain parameters. Thus, the uncertainty associated with $\tilde{C}_{S,\Delta x}$ is reflected by a fuzzy quantification with a triangular membership function. The above result represents the apex of this membership function.

The surface chloride concentration cannot be lower than for a matrix without binding capacity, in which only the pores are filled with the saline solution. According to Eq. (7), this yields a lower bound of 1.30% by mass of binder.

The upper bound of the fuzzy value for the surface chloride concentration can be determined based on experiments in which specimens were exposed to saline solution with $c_{Cl} = 165$ g/l [8]. Since the binding capacity of the matrix increases with increasing salinity, the experimental results provide a conservative upper bound for the actual chloride binding. To avoid being overconservative, the experimentally derived value is adjusted to account for a salinity of the pore solution of 20 g/l instead of 165 g/l. This results in an upper bound of the surface chloride concentration of 10.05% by mass of binder.

2.3. Age factor $\tilde{n}_{cf}$

Chloride diffusion in cementitious materials is a time-dependent phenomenon characterised by a decrease of the diffusion coefficient over time. While this time dependence is not fully understood at present, ongoing hydration and time-dependent chloride binding are generally considered to be the primary causes [11–14].

The age factor used to describe this phenomenon is usually determined empirically based on a large number of data from short- and long-term exposures. Especially for long-term exposure, there are often very few data available. For this reason only the age factors for concrete with ordinary Portland cement and concrete containing silica fume were quantified based on such data in the DuraCrete project. In contrast, the age factors for fly ash and slag cement concrete were determined based on expert judgement. It is obvious that for new materials such as SHCC even less information is available, which complicates a reliable quantification of the age factor.

Since ongoing hydration is one of the primary reasons for changes of the diffusion coefficient, data obtained from RCM-Tests [15] on concrete at young ages has been used to supplement results of long-term field observations [16]. In the absence of such field data for SHCC, a first estimate for the age factor can be obtained from RCM-Test results. For the SHCC composition given in Table 2, RCM-Tests were performed on specimens aged between 7 and 119 days. From the development of the chloride migration coefficient, an age factor of $n_{cf} = 1.23$ was determined [17].

To date it has not been possible to establish clear correlations between parameters such as binder content or water-to-cement ratio [18,19] and the age factor. Nonetheless, it is helpful to supplement the RCM-Test results with values for the age factor of ordinary fly ash concrete.

For the apparent diffusion coefficient

$$D_a = k_e k_t k_c D_{RCM,0} \left(\frac{t'_0}{t + t'_{ex}} \right)^n, \tag{9}$$

Gehlen [7] quantified the age factor of ordinary fly ash concrete as beta-distributed with a mean value of $m = 0.60$, a standard deviation of $s = 0.15$, and lower and upper bounds of 0.0 and 1.0. This result is in good agreement with typical values to be found in the literature, which range from 0.60 to 0.70 [12,13,20]. It also agrees well with the expert opinion-based beta-distribution with a mean value $m = 0.69$ in the DuraCrete project [18]. The largest outliers were reported in [12], in which values between 0.48 and 0.91 for the age factor based on experiments with short exposure times between 40 and 365 days were determined.

As outlined in Part 1 of the publication, age factors determined for Eq. (9) need to be converted to be used in conjunction with Eqs. (4) and (5). Results of the conversion are given in Table 3.

With small values for n_{cf} resulting in a smaller reduction of the diffusion coefficient over time, it is reasonable and conservative to assume that the outliers reported for ordinary fly ash concrete are also possible realisations for SHCC. However, the possibility that the age factor shows values typical for ordinary fly ash concrete or determined from RCM-Tests on SHCC specimens is significantly higher. Thus, the age factor may be quantified as shown in Fig. 1 as

$$\tilde{n}_{cf} = \langle 0.60; 0.77; 1.23; 1.42 \rangle. \tag{10}$$

2.4. Chloride diffusion coefficient $\tilde{D}_{ex,0,cf}$

The diffusion coefficient of the crack-free material under laboratory conditions $\tilde{D}_{ex,0,cf}$ was determined based on immersion experiments according to NT BUILD 443 [21]. For crack-free specimens and areas with few or no apparent cracks in pre-strained specimens, the results given in Table 4 were obtained.

The diffusion coefficients $D_{ex,\xi,cf}$ given in Table 4 must not be confused with $D_{ex,0,cf}$ determined at the reference time $t'_0 = 28$d. This result is due to the time-dependence of the diffusion coefficient. However, $D_{ex,0,cf}$ can be determined from those values according to

$$D_{ex,0,cf} = \left(\frac{t'_0}{t'_\xi} \right)^{n_{cf}} D_{ex,\xi,cf}, \tag{11}$$

if the age factor n_{cf} is known (cf. Table 4).

From these results, it is possible to quantify the mean value of the fuzzy-probabilistic variable $\tilde{D}_{ex,0,cf}$ as a fuzzy value with a trapezoidal membership function $\mu_{\tilde{m}}(D_{ex,0,cf})$. The highest and lowest values for a given realisation of $\tilde{n}_{cf}$ define the upper and lower boundaries ($\mu = 0$) of possible realisations for the diffusion coefficient. The range of values for the highest possibility of realisation ($\mu = 1$) is given by the second-highest and -lowest tabulated values, respectively (cf. Fig. 2).

Table 3
Age factor conversion.

n	$n_{cf}\,(t'_{ex},t)$	
	$t'_{ex} = 50$ d, $t = 20$ years	$t'_{ex} = 50$ d, $t = 100$ years
0.48	0.63	0.60
0.60	0.81	0.77
0.91	1.42	1.39

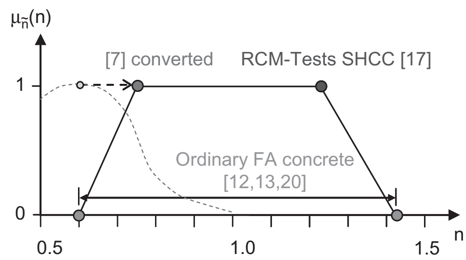

Fig. 1. Membership function of the age factor $\tilde{n}_{cf}$.

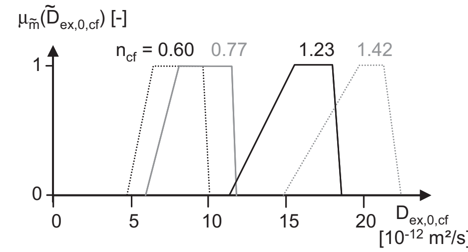

Fig. 2. Membership function of the fuzzy mean value $\tilde{m}$ of the diffusion coefficient $\tilde{D}_{ex,0,cf}$ for $\tilde{n}_{cf} = \langle 0.60; 0.77; 1.23; 1.42 \rangle$.

Since this quantification of the mean value is based on the experimental procedure as outlined in NT BUILD 443, the quantification of the stochastic uncertainty given there can be assumed to apply for $D_{ex,0,cf}$. Thus, the variable is assumed to be normally distributed with a coefficient of variation CoV = 0.15.

2.5. Critical chloride concentration C_{crit}

In line with the fib Model Code [22], the critical chloride concentration C_{crit} is defined as that total chloride concentration at which the steel reinforcement is depassivated and steel corrosion may begin. It thus defines the end of the initiation stage and the beginning of corrosion propagation.

As a recent review of the state-of-the-art [23] showed, there is currently no general agreement on a critical chloride concentration in ordinary concrete. Values reported in the literature range from 0.04% to 1.30% total chloride by weight of cement under submerged conditions, and despite significant efforts no clear correlation between binder types and other aspects of the mixture composition and C_{crit} could be established.

The fib Model Code, the DARTS project [24] and Gehlen [7] quantify C_{crit} for ordinary concrete based on two experimental investigations and literature reviews [25,26] as beta-distributed with lower and upper boundaries of 0.2% and 2.0%, a mean value of m = 0.60% and a standard deviation of s = 0.15%. However, under permanent submersion the propagation of corrosion is very slow, and for this reason higher values for C_{crit} may be permissible [7]. This result would suggest a higher mean value and is reflected in the quantifications in [27] (Normal distribution, m = 2.0%, s = 0.15%) and the DuraCrete project [18] (Normal distribution, m = 1.60%, s = 0.20%).

So far, no systematic research has been carried out to determine C_{crit} in SHCC. Thus, its quantification in this example is based only on investigations of ordinary concrete. Due to the lack of further information, it was decided to adopt the fib Model Code quantification for ordinary concrete, which is the most conservative of the given stochastic quantifications and the only one with a lower bound, which is more realistic than the possibility of negative values for C_{crit} in the other quantifications. While some threshold values below this lower bound are reported in [23], they were determined using methods deemed unreliable by the authors, and it was decided to disregard them in the quantification for C_{crit} for SHCC.

Considering that the decision to adopt the fib Model Code values is based on expert judgement, it may be argued that this should be reflected in a fuzzy or fuzzy-probabilistic quantification. While not realised here, this could be done in a similar fashion as has been done for the age factor.

2.6. Further variables

The *age at first exposure* t'_{ex} = 50 d was chosen based on a Danish report recommending an age at first exposure t'_{ex} > 42 d for ordinary Portland cement concrete [14]. In the absence of further information and in line with customary assumptions, the *initial chloride content* C_0 prior to exposure to seawater has been assumed to be 0% by mass of binder. For the same reason, the *influence of curing* has been ignored in this example. Furthermore, the depth of the *convection zone* in the permanently submerged condition is Δx = 0 mm.

For the scatter of the *cover depth c*, no substantial differences between RC and R/SHCC members and structures are expected. Thus, it can be quantified based on the fib Model Code as being log-normal distributed and, assuming good execution quality, having a standard deviation of 6 mm.

As in the DuraCrete concept, the temperature influence is accounted for with the help of an *environment factor*

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right) \quad (12)$$

where b_e is the regression parameter quantified for ordinary Portland cement concrete [7], T_{ref} the reference temperature and T_{real} is the actual temperature according to Chapter 2.1. Since this influence is independent of the mix design, no changes are necessary to apply it to SHCC.

The *transfer factor* k_t = 1.0 is a regression parameter to determine the age factor [7]. Since $\tilde{n}_{cf}$ has been determined partly based on this source but without any other regression analysis, no changes with respect to the parameter are required.

Table 4
Experimentally determined diffusion coefficients $D_{ex,\xi,cf}$ and surface chloride concentrations C_s at the age t'_ξ for crack-free (P·) specimens and near crack-free areas of pre-strained specimens (A, B) [8,17].

Specimen	t'_ξ (d)	$D_{ex,\xi,cf}$ (10^{-12} m²/s)	C_s (% by mass of binder)	$D_{ex,0,cf}$ (10^{-12} m²/s)			
				n_{cf} = 0.60	n_{cf} = 0.77	n_{cf} = 1.23	n_{cf} = 1.42
A	120	4.58	8.56	8.69	10.37	16.59	20.07
B	121	5.09	8.97	9.68	11.57	18.55	22.44
P1	97	5.71	7.70	10.05	11.77	17.94	21.30
P2	119	4.54	8.36	8.59	10.24	16.36	19.77
P3	154	2.00	9.47	4.70	5.97	11.38	14.82
P4	154	2.74	7.87	6.44	8.18	15.59	20.31

Table 5
Quantification of input variables for SHCC submerged in a North Sea marine environment.

Nr	Variable	Unit	Distribution function	Mean value	CoV
1	C_{crit}	% by mass of binder	Beta, a = 0.2, b = 2.0	0.60	0.25
2	C_0	% by mass of binder	–	0	–
3	$\tilde{C}_{S,\Delta x}$	% by mass of binder	–	<1.30; 2.91; 10.05>	–
4	c	mm	Log-normal	50	0.12
5	Δx	mm	–	0	–
6	$\tilde{n}_{cf}$	–	Fuzzy	<0.60; 0.77; 1.23; 1.42>	
7	$\tilde{D}_{ex,0,cf}$	10^{-12} m^2/s	Normal	n_{cf} = 0.60: <4.40; 6.44; 9.68; 10.05> n_{cf} = 0.77: <5.97; 8.18; 11.57; 11.77> n_{cf} = 1.23: <11.38; 15.59; 17.97; 18.55> n_{cf} = 1.42: <14.82; 19.77; 21.30; 22.44>	0.15
8	b_e (k_e)	K	Normal	4800	0.15
9	T_{ref} (k_e)	K	–	293	–
10	T_{real} (k_e)	K	Normal	283	0.02
11	k_t	–	–	1	–
12	k_c	–	–	1	–
13	t'_0	d	–	28	–
14	t'_{ex}	d	–	50	–

3. Results and discussion

3.1. Chloride concentration

With the input variables given in Table 5, the time-dependent total chloride concentration at the depth of the reinforcement $\tilde{C}(c,t)$ was determined for ages at first exposure t'_{ex} = 25, 50, 75 d. Only very small differences between the results for different t'_{ex} could be observed. However, these results cannot be extrapolated to shorter times until first exposure. The results for t'_{ex} = 50 d are shown in Figs. 3 and 4. As in Fig. 5, only the upper boundaries of the fuzzy result value for each α-level are shown since the values of the lower boundaries are so small that they are hidden by the time-axis. It can be seen that the results entail significant non-stochastic as well as stochastic uncertainty. This is not surprising, considering the uncertainty of the input variables.

According to Table 5, the mean value of the critical chloride concentration is m_{Ccrit} = 0.60% by mass of binder with a lower bound of 0.20% for the probability density function. Thus, for lower values of the membership function $\mu_{\tilde{C}(c,t)}$ there is a significant likelihood that the limit state function $\tilde{g}(c,t)$ becomes negative after less than 30 years. This likelihood is expressed as the probability of failure $\tilde{p}_f$.

3.2. Probability of failure

The probability of failure expresses the stochastic uncertainty if $g(c,t) < 0$ with a certain value. If imprecision and variability are quantified with fuzzy random input variables, the resulting probability of failure is also fuzzy (cf. Fig. 7 in Part 1). Thus, imprecision remains visible in Fig. 5, which shows that the possibility exists that the probability of failure after 100 years of exposure is close to unity, which would mean certain failure. However, it is equally possible that the probability of failure $\tilde{p}_f < 10^{-6}$, which is much smaller than the acceptable failure probability $\tilde{p}_f = 10^{-1}$ recommended in the fib Model Code for this limit state.

This pronounced non-stochastic uncertainty might suggest that the proposed durability concept does not yield meaningful results. In fact, the opposite is true: It could be shown that even with a very limited database, a transparent determination of the probability of failure is possible. Still further, the upper bound of $\tilde{p}_f(\mu = 0)$ is realised for n_{cf} = 0.60, the conservative lower bound for the age factor based on an outlier reported for ordinary fly ash concrete. The possibility is much higher ($\mu = 1$) that $\tilde{p}_f < 10^{-2}$, which is realised for $n_{cf} \geqslant 0.77$. This value is still much lower than the experimentally determined age factor n_{cf} = 1.23 for the SHCC in question.

From these observations it is obvious that a reduction of the non-stochastic uncertainties associated with the age factor is likely to result in significantly reduced values for the upper boundary of the fuzzy failure probability. However, to target future research efforts most effectively, the dominant variables must be identified with the help of sensitivity analysis.

3.3. Sensitivity analysis

To assess the sensitivity of the chloride concentration $\tilde{C}(c,t)$ to changes of the input variables, the coefficients of correlation between the input variables and the resulting chloride concentration $r_{\tilde{C}(c,t)x_i}$ (see Chapter 4 in Part 1) were computed.

These coefficients of correlation must be interpreted with some caution since they only yield linear correlations. Furthermore, they cannot be determined for variables with only fuzzy uncertainty, and the fuzzy uncertainty of any input variable results in fuzzy coefficients of correlation. Hence, the interpretation of the results given in Fig. 6 is not straightforward. It is worthy of note but not visible in the figure, for instance, that the highest correlation for c and T_{real}, respectively, was achieved for n_{cf} = 1.42.

It is thus helpful to consider the fuzzy variables as equally distributed over the interval defined by the membership function. In this case, this means $C_{S,\Delta x}$ = [1.30; 10.05], n_{cf} = [0.60; 1.42], $m_{\tilde{D}_{ex,0,cf}}(n_{cf} = 0.60)$ = [4.40; 10.05], $m_{\tilde{D}_{ex,0,cf}}(n_{cf} = 0.77)$ = [5.97; 11.77], $m_{\tilde{D}_{ex,0,cf}}(n_{cf} = 1.23)$ = [11.38; 18.55] and $m_{\tilde{D}_{ex,0,cf}}(n_{cf} = 1.42)$ = [14.82; 22.44].

This quantification leads to certain coefficients of correlation (cf. Fig. 7) but gives undue weight to extreme realisations of fuzzy variables and may thus result in an overestimation of the weight of these variables. By quantifying stochastic variables equally distributed on the interval [$m - 3s$; $m + 3s$] with m: the mean and s: the standard deviation of the respective variable, this undue weight may to a certain degree be ameliorated (cf. Fig. 8).

As seen in Figs. 7 and 8, the sensitivity of the chloride concentration with respect to changes in the input variables is time-dependent. Especially the correlation between $\tilde{C}(c,t)$ and $\tilde{n}_{cf}$ increases over time.

The absolute values of the coefficients of correlation can be normalised, which allows their ranking according to relative weight. Fig. 9 shows the result for the same variable quantifications used to generate Fig. 8 and t = 90 years. The influence of the considered range of value of the input variables on the correlation coefficient can be seen by comparing Fig. 9a and b, for which only the quantification of n_{cf} has been changed, with the influence of variables quantifying material properties becoming smaller as the age factor increases.

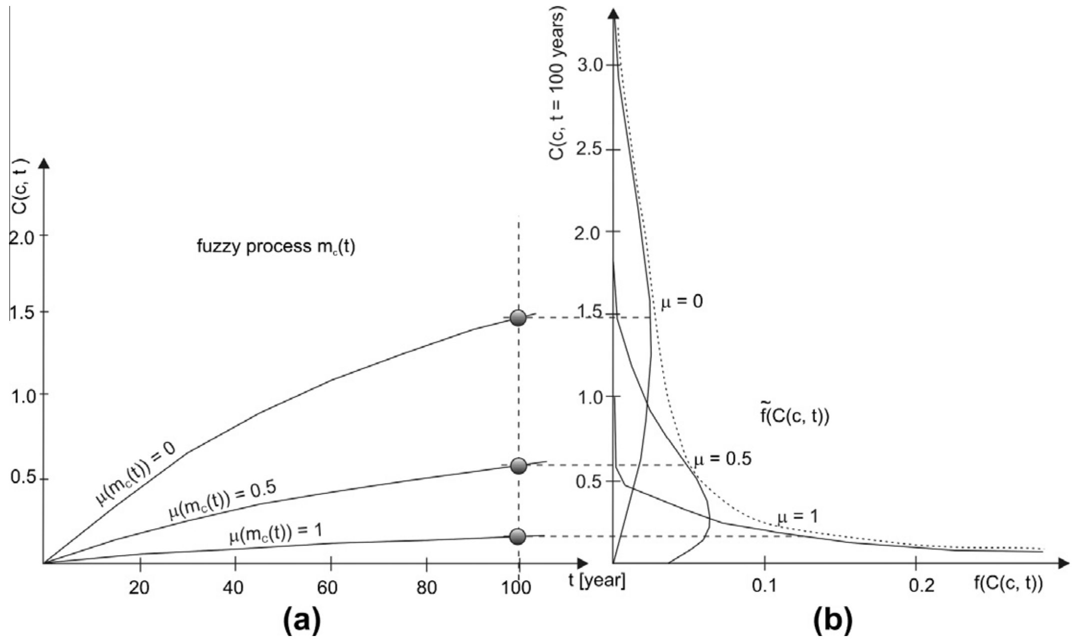

Fig. 3. (a) Fuzzy mean value of the total chloride concentration at $\tilde{x}$ = 50 mm from the surface for t'_{ex} = 50 d and (b) Fuzzy probability density distribution of the chloride concentration $\tilde{C}(c, t = 100\text{ years})$ for the mean value.

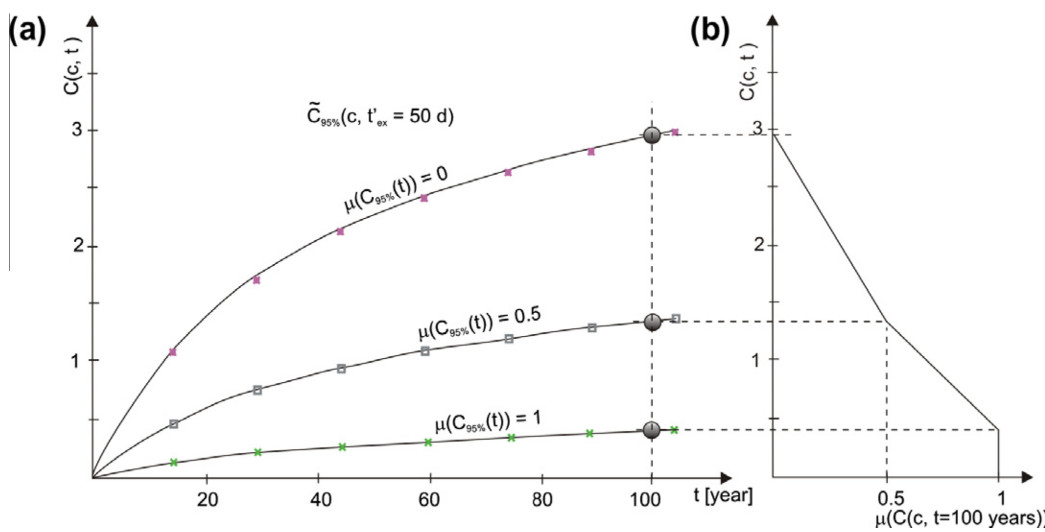

Fig. 4. (a) Fuzzy 95% quantile of the total chloride concentration at $\tilde{x}$ = 50 mm from the surface for t'_{ex} = 50 d and (b) membership function for t = 100 years.

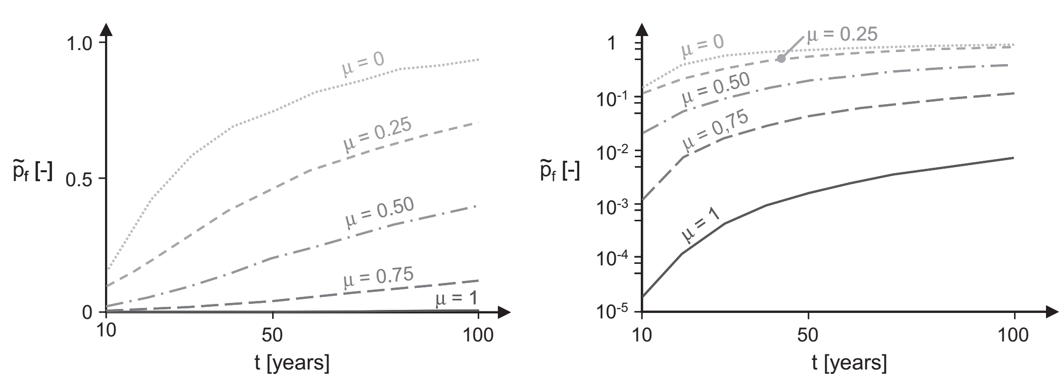

Fig. 5. Development of the probability of failure $\tilde{p}_f$ with the time of exposure t.

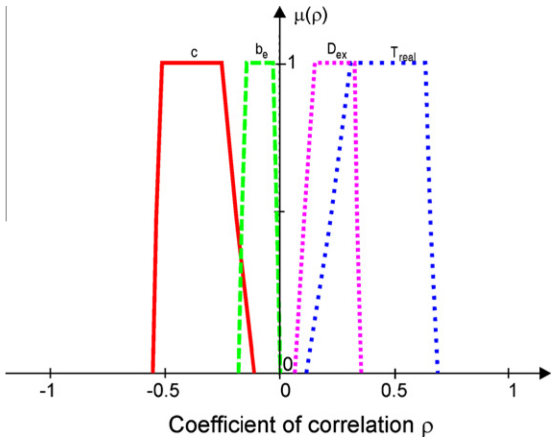

Fig. 6. Fuzzy coefficient of correlation ρ of input variables and the chloride concentration $C(c, t)$ for t'_{ex} = 50 d, t = 50 years and all other variables as per Table 5.

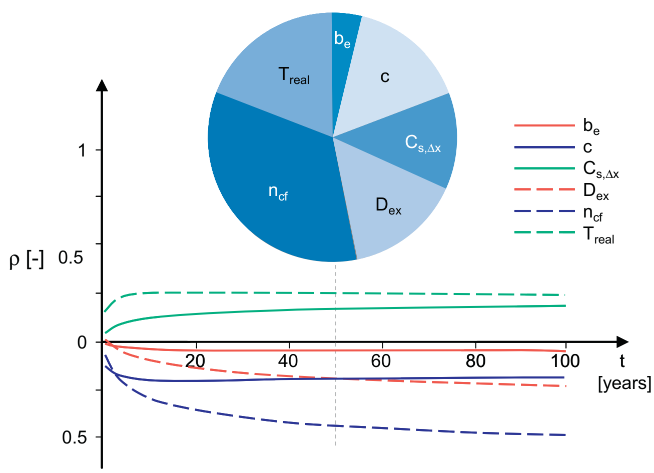

Fig. 7. Coefficient of correlation ρ of input variables and $C(c, t)$ for t'_{ex} = 50 d and the input variables with all fuzzy variables equally distributed over the interval defined by the membership function and all probabilistic variables as per Table 5.

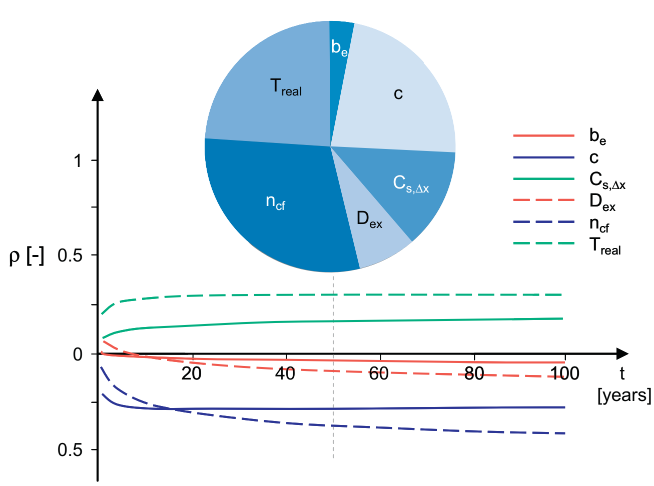

Fig. 8. Coefficient of correlation ρ of input variables and $C(c, t)$ for t'_{ex} = 50 d and the input variables with all fuzzy variables equally distributed over the interval defined by the membership function and all probabilistic variables equally distributed over the interval $[m - 3s; m + 3s]$.

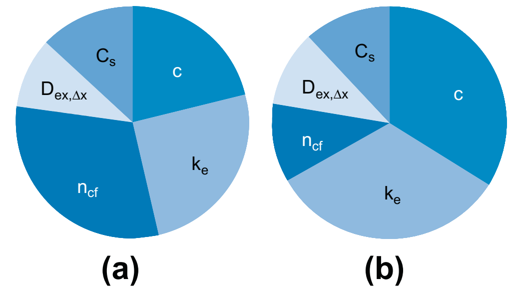

Fig. 9. Normalised absolute values of the coefficient of correlation of $C(c, t)$ for t'_{ex} = 50 d and t = 90 years and the input variables for all fuzzy variables equally distributed over the interval defined by the membership function and all probabilistic variables equally distributed over the interval $[m - 3s; m + 3s]$. (a) n_{cf} = [0.60; 1.42], and (b) n_{cf} = [1.20; 1.42].

It is evident from the remarks and figures above that the results of a sensitivity analysis must be interpreted in light of the chosen method and value range of input parameters. For instance, the actual correlation between individual input variables and $\tilde{C}(c, t)$ may be stronger than suggested by the results in Figs. 6–9 due to non-linear effects not reflected in the coefficient of correlation.

Nonetheless, some conclusions can be drawn from the results given in Figs. 6–9. For high values of $\tilde{n}_{cf}$, the cover depth and the temperature, both not material-specific, are the dominant variables while otherwise the chloride concentration is most sensitive to changes in the age factor. This finding supports the results of Chapter 3.2 and is in good agreement with results for ordinary fly ash concrete reported elsewhere [7,24]. Thus, research efforts aimed at reducing the uncertainty associated with this variable are likely to have the biggest impact on reducing the uncertainty associated with the probability of failure $\tilde{p}_f$.

Other variables which are well correlated with the chloride concentration $\tilde{C}(c, t)$ are the cover c and the temperature T_{real}, while $\tilde{C}(c, t)$ seems to be less sensitive to changes in the most-studied variable, the diffusion coefficient.

4. Conclusions

As outlined in Part 1 of this work, the inherent durability of SHCC and other new materials with similarly promising properties such as textile-reinforced concrete (TRC) [28] can be best demonstrated using a performance-based durability concept. In the first part of this treatise a fuzzy-probabilistic durability concept for SHCC exposed to chlorides was introduced, which is a suitable template for other load cases as well as for durability concepts for materials like TRC. In this second part, the durability concept was applied to a crack-free R/SHCC member submerged in seawater.

Input variables were transparently quantified based on the limited information available for chloride ingress into SHCC and on expert assessment of information on chloride ingress in ordinary fly ash concrete and the underlying physical and chemical processes.

From these the accumulation of chlorides at the depth of the steel reinforcement over time and the time-dependent fuzzy probability of the onset of corrosion propagation were calculated. Still further, a sensitivity analysis was performed for the chloride concentration to determine the most critical variables.

It was found that the chloride concentration at the depth of the reinforcement is most sensitive to the age factor $\tilde{n}_{cf}$ and the non-material-specific cover depth and temperature, while the much more widely investigated diffusion coefficient is of lesser importance.

The failure probability $\tilde{p}_f$ shows significant non-stochastic uncertainty, currently precluding the concept from being used as a practical design tool. This is especially the case since the end of the service life of a member is typically deemed to be reached if the highest possible, and, thus, most conservative, realisation of $\tilde{p}_f$ exceeds the maximum permissible failure probability.

The age factor exhibits the highest uncertainty due to a lack of information of the dominant variables. Thus, targeted research to reduce the information deficit regarding the age factor is likely to have the most pronounced effect on the probability of failure. However, further investigations are required to determine if these conclusions hold for other realistic combinations of input variables. Based on the results of such a parameter study, it will be possible systematically to target experimental investigations so as to yield the maximum benefit with regard to durability design.

In addition, although disregarded in this example, significant effort will be required to determine and describe the influence of cracks on chloride ingress as transparently and precisely as required.

Despite the uncertainty associated with the failure probability, the significant potential of the approach is evident: It could be shown that fuzzy parameter quantification is practicable and transparent and that the concept allows the determination of the desired output variables, in this case the chloride concentration $\tilde{C}(c,t)$ and the probability of steel corrosion $\tilde{p}_f$. With the help of the results of sensitivity analyses, it is furthermore possible to optimally target future research efforts to reduce the uncertainty of $\tilde{p}_f$. This approach will help develop the concept presented in this paper into a practicable service life design tool.

References

[1] Jun P, Mechtcherine V. Behaviour of strain-hardening cement-based composites (SHCC) under monotonic and cyclic tensile loading: Part 1 – Experimental investigations. Cem Concr Compos 2010;32:801–9.
[2] DuraCrete, Probabilistic performance based durability design of concrete structures. The European Union – Brite Euram III, Project BE95-1347, Report R15; 2000.
[3] Mechtcherine V, Altmann F. Durability of structural elements and structures. In: Van Zijl GPAG, Wittmann FH, editors. Durability of strain-hardening fibre-reinforced cement-based composites (SHCC). Springer; 2011. p. 89–112.
[4] Mechtcherine V. Towards a durability framework for structural elements and structures made of or strengthened with high-performance fibre-reinforced composites. Constr Build Mater 2012;31:94–104.
[5] Rokugo K, Kanda T, Yokota H, Sakata N. Applications and recommendations of high performance fiber reinforced cement composites with multiple fine cracking (HPFRCC) in Japan. Mater Struct 2009;42:1197–208.
[6] Becker GA, Schulz A. Atlas of North Sea surface temperatures. Weekly and monthly means for the period 1969–1993. German J Hydrography 2000;51:5–79.
[7] Gehlen C. Probabilistische Lebensdauerbemessung von Stahlbetonbauwerken. Schriftenreihe des Deutschen Ausschusses für Stahlbeton, Heft 510. Berlin: Beuth Verlag; 2000.
[8] Altmann F, Mechtcherine V. Modelling chloride ingress into cracked and crack-free strain-hardening cement-based composites (SHCC). In: Ferreira RM, Gulikers J, Andrade C, editors. Modelling the durability of reinforced concrete. Guimaraes: RILEM Publications S.A.R.L.; 2009. p. 75–83.
[9] Tang L. Chloride transport in concrete – Measurement and prediction. PhD Thesis, Chalmers University of Technology; 1996.
[10] DIN 1045-2:2008-08. Concrete, reinforced and prestressed concrete structures – Part 2: Concrete – Specifications, properties, production and conformity – Application rules for DIN EN 206-1.
[11] Tang L. Engineering expression of the ClinConc model for prediction of free and total chloride ingress in submerged marine concrete. Cem Concr Res 2008;38:1092–7.
[12] Nokken M, Boddy A, Hooton RD, Thomas MDA. Time dependent diffusion in concrete – three laboratory studies. Cem Concr Res 2006;36:200–7.
[13] Stanish KD, Thomas M. The use of bulk diffusion tests to establish time-dependent concrete chloride diffusion coefficients. Cem Concr Res 2003;33:55–62.
[14] Nilsson L-O, Poulsen E, Sandberg P, Sorensen HE, Klinghoffer O. HETEK, Chloride penetration into concrete – State of the art, transport processes, corrosion initiation, test methods and prediction models, Danish Road Directorate, Report No. 53; 1996.
[15] NT BUILD 492:1999-11. Concrete, mortar and cement based repair materials: Chloride migration coefficient from non-steady state migration experiments.
[16] Gulikers J. A critical review of the mathematical modelling of chloride ingress into concrete and the derivation of input data. In: Baroghel-Bouny V, Andrade C, Torrent R, Scrivener K, editors. International RILEM workshop performance based evaluation and indicators for concrete durability, vol. PRO 47. RILEM Publications S.A.R.L.; 2007. p. 165–75.
[17] Altmann F. A durability concept for strain-hardening cement-based composites. Doctoral Thesis, Technische Universität Dresden, 2012.
[18] DuraCrete, Statistical quantification of the variables in the limit state function, The European Union – Brite Euram III, Project BE95-1347, Report R9; 2000.
[19] Audenaert K, Yuan Q, De Schutter G. On the time dependency of the chloride migration coefficient in concrete. Constr Build Mater 2010;24:396–402.
[20] Thomas MDA, Bamforth PB. Modelling chloride diffusion in concrete – Effect of fly ash and slag. Cem. Concr. Res. 1999;29:487–95.
[21] NT BUILD 443:1995-11. Concrete, hardened: accelerated chloride penetration.
[22] International federation for structural concrete (fib), Model code for service life design, fib Bulletin, 34, Lausanne; 2006.
[23] Angst U, Elsener B, Larsen CK, Vennesland Ø. Critical chloride content in reinforced concrete – A review. Cem Concr Res 2009;39:1122–38.
[24] Gehlen C, Kapteina G. DARTS – Durable and Reliable Tunnel Structures, Data, The European Union – GROWTH 2000, Project GRD1-25633; 2004.
[25] Breit W. Untersuchung zum kritischen korrosionsauslösenden Chloridgehalt. PhD Thesis, RWTH Aachen; 1997.
[26] Glass GK, Buenfeld NR. Chloride threshold levels for corrosion induced deterioration of steel in concrete. In: Nilsson L-O, Ollivier JP, editors. RILEM international workshop on chloride penetration into concrete, vol. PRO 2. Saint-Remy-Les-Chevreuse: RILEM Publications S.A.R.L.; 1995. p. 429–40.
[27] Lindvall A. Environmental actions on concrete exposed in marine and road environments and its response. PhD Thesis, Chalmers University of Technology; 2003.
[28] Mechtcherine V, Lieboldt M. Permeation of water and gases through cracked textile reinforced concrete. Cem Concr Compos 2011;33:725–34.