A novel durability design approach for new cementitious materials: Modelling chloride ingress in strain-hardening cement-based composites

F. Altmann & V. Mechtcherine
Institute of Construction Materials, TU Dresden, Dresden, Germany
U. Reuter
Department of Civil Engineering, TU Dresden, Dresden, Germany
Formerly: Institute of Statics and Dynamics of Structures, TU Dresden, Dresden, Germany

ABSTRACT: To fully utilise the advantageous durability properties of new cementitious materials such as fibre-reinforced Strain-Hardening Cement-based Composites (SHCC), a performance-based durability design approach is required. For crack-free ordinary concrete first promising concepts exist, e.g. the DuraCrete model. However, the parameters of these models, which were quantified for ordinary concrete, cannot be applied to SHCC due to its significantly different composition. As multiple cracking with limited crack width under tensile load is a characteristic material property of SHCC, any durability model for this material furthermore has to consider the cracked state. In this paper a novel durability design approach is presented exemplary for chloride ingress in SHCC. The developed approach takes into account the limited availability of relevant data for new materials, which prevents a reliable stochastic quantification of model parameters. The DuraCrete ingress model was adapted for SHCC with the help of fuzzy-probability theory, which allows the quantification of parameters using expert knowledge even if the data basis is very limited.

1 INTRODUCTION

Strain-hardening cement-based composites (SHCC) are a new group of materials with superior ductility and promising durability properties (Li 2003; Mechtcherine & Schulze 2005). SHCC displays a high strain capacity due to the gradual formation of a large number of fine, well-distributed cracks. The width of these cracks is typically less than 0.1 mm. Figure 1 shows a typical stress-strain curve for SHCC with 2.2% by volume of polymeric fibre and corresponding average crack widths as a function of the induced strain.

This new material is suitable for non-structural and structural applications and will likely be used in combination with ordinary steel reinforcement (Mechtcherine & Altmann 2008). According to Li (2003) one target application for SHCC are structures requiring durability under severe environmental loading. In such cases the protection of steel reinforcement from corrosion, for instance due to chloride ingress, is a key durability requirement. Additionally, chloride has a detrimental effect on the fibre-matrix bond properties of the composite and consequently

Figure 1. Typical stress-strain and strain-crack width curves for SHCC.
et al. (2007) conducted immersion and ponding tests on cracked and crack-free SHCC as well as mortar specimens. They observed a much lower chloride diffusion coefficient for SHCC than for mortar, both in the cracked and crack-free state. The authors further found the diffusion coefficient of SHCC to be proportional to the observed number of cracks. They attributed their findings to a higher content of cementitious material, a low water-binder ratio, the self-limiting crack width of SHCC and self-healing.

To design durable structures with high-performance composites such as SHCC, an appropriate durability design concept is required. Most current concrete codes like Eurocode 2 or DIN 1045 prescribe a deterministic design approach. Structures designed according to the deemed-to-satisfy rules of these standards will have an acceptably long, but not specified lifetime. It has been long recognised that this approach is unsatisfactory, and that a performance-based durability design approach is required to achieve the required service life with a sufficient degree of probability while fully utilising the durability properties of the cementitious material.

For ordinary concrete a promising probabilistic design concept was developed in the European DuraCrete project (2000b). It uses simple analytical formulas to describe corrosion processes. The model parameters are quantified stochastically to reflect the scatter observed in laboratory and field experiments, thus allowing a probabilistic modelling of the considered processes. A similar concept is required for SHCC to allow the best possible utilisation of the material’s durability properties.

2 NOVEL DURABILITY DESIGN APPROACH

In its current form the DuraCrete model cannot be applied to SHCC, as the composition of SHCC (refer Table 1) is very different from that of ordinary concrete, for which the parameters in the DuraCrete model were quantified. SHCC does not contain coarse aggregates and the associated “transport highways” formed by the contact zone between matrix and aggregates. However, it contains short fibres, which might have an—as yet unquantified—influence on the transport of aggressive agents. Furthermore, SHCC has usually more binder than ordinary concrete, giving the material a higher binding capacity for some corrosive agents such as chloride ions. Another limitation of the DuraCrete model is the fact, that it is only applicable to crack-free concrete. SHCC, however, is specifically designed to exhibit multiple, well-distributed cracks of self-limited width in the serviceability state. Thus a durability design concept for this new material needs to also address the cracked state.

To describe chloride ingress in concrete, the DuraCrete model uses the empirical formula described in Chapter 4. The model parameters are quantified stochastically for various material compositions and environmental conditions based on a large number of laboratory and field observations. For a new material such as SHCC only limited data is available, and great research efforts would be required to obtain sufficient data for a reliable stochastic parameter quantification. In the case of SHCC this is exacerbated by the need to also model the cracked state, which requires the quantification of the effects of additional parameters. It is unlikely that the required data will be available in the foreseeable future.

<table>
<thead>
<tr>
<th>Table 1. Exemplary compositions for SHCC [kg/m³].</th>
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</thead>
<tbody>
<tr>
<td>(Sahmaran et al. 2007)</td>
</tr>
<tr>
<td>Portland Cement</td>
</tr>
<tr>
<td>Fly Ash</td>
</tr>
<tr>
<td>Fine Sand</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Super Plasticizer</td>
</tr>
<tr>
<td>Viscosity Agent</td>
</tr>
<tr>
<td>PVA Fibre</td>
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</table>

Figure 2. Schematic representation of the approach used for the development of a performance-based model for chloride ingress in strain-hardening cement-based composites (SHCC).
Sickert et al. (2005) showed for steel corrosion due to chloride ingress that the fuzzy-probability theory allows a transparent quantification of expert knowledge in combination with limited data. Thus the shortcomings of the DuraCrete model can be overcome with the approach shown schematically in Figure 2. Using an extended DuraCrete model that includes the influence of cracks on the transport properties of SHCC, it is thus possible to develop a fuzzy-probabilistic chloride ingress model with the available information.

With the definition of limit states and permissible failure probabilities, it will in the future be possible to develop this approach into a fuzzy-probabilistic service life design concept for steel-reinforced SHCC structures exposed to attack by chlorides.

3 FUZZY-PROBABILITY THEORY

3.1 Fuzzy randomness

If insufficient data for a stochastic description of the random parameter properties is available, this lack of knowledge may be interpreted as non-stochastic or fuzzy uncertainty. Random and fuzzy uncertainties exist simultaneously, resulting in fuzzy-randomly distributed parameters (Möller & Beer (2004). The likelihood that such parameters attain a certain value is described as fuzzy probability.

Fuzzy uncertainty may also be expressed as the possibility—as opposed to the probability in the case of random uncertainty—that a parameter assumes a certain value. This possibility can be quantified with the help of a membership function for this parameter. Figure 3 shows a trapezoidal membership function. Other curves may be defined, but usually simple trapezoidal or triangular functions are the most useful ones.

Fuzzy random parameters may thus be quantified by defining the variables of their probability functions as fuzzy variables. In contrast to the common approach of making conservative assumptions for these variables, fuzzy probability theory clearly separates hard data from expert knowledge and thus allows a transparent and consistent parameter quantification. If, for instance, only two experimental values are available for the chloride diffusion coefficient of a certain concrete mix, this does not allow a probabilistic quantification. Assuming further for the sake of simplicity, that the diffusion coefficient is normally distributed with a known standard deviation, only the mean value has to be modelled as a fuzzy variable. Using the trapezoidal membership function in Figure 3, the values of \( a, b, c \) and \( d \) can be defined using expert knowledge. With \( D > 0 \) it is \( a = 0 \), and the two experimental values define \( b \) and \( c \). As the diffusion coefficient of chloride in concrete is less than in the bulk pore fluid, \( d \) is defined by the bulk fluid diffusion coefficient. This is a conservative definition and additional knowledge may well yield a less uncertain distribution of the expected value for the diffusion coefficient. The corresponding fuzzy probability distribution function is shown in Figure 4.

Fuzzy and fuzzy random input variables can be processed in a computational model using fuzzy and fuzzy stochastic analysis respectively. Both are described in detail in Möller & Beer (2004) and Möller & Reuter (2007).

3.2 Model uncertainty

Empirical models, such as the one developed in the DuraCrete project for chloride ingress, are mathematical fits to observations and have no clear physical meaning. Due to this model uncertainty, predictions about future behaviour past the timeframe for which data is available, must be interpreted with great caution (ChlorTest 2005).

If fuzzy variables are appropriately defined, this model uncertainty is reflected in the results of a fuzzy random analysis. Thus the approach outlined below can give valuable information, albeit with significant non-stochastic uncertainty, on chloride ingress in SHCC well into the future.

4 ADAPTING THE DURACRETE MODEL

4.1 Fundamentals

In the past a number of different models for chloride ingress in concrete have been developed, all of which have significant shortcomings. A good overview and
Discussion was compiled in the ChlorTest project (2005). The empirical DuraCrete model (2000c) does not describe the actual physical and chemical processes, but it is simple and well-documented and significant efforts have been made to quantify its parameters. For these reasons it was chosen at the present stage as the platform for the development of a model for SHCC. The DuraCrete model is based on Fick’s second law and time-dependent diffusion coefficients must be used in Equation 2:

\[
D_a = D_0 \frac{1}{1-n} \left[ \left( \frac{t_{ex}}{t} \right)^{1-n} - \left( \frac{t_{ex}}{t'} \right)^{1-n} \right] \left( \frac{t_{ex}}{t} \right)^n
\]

4.3 Apparent diffusion coefficient in the modified DuraCrete model for SHCC

The above formulas were derived for chloride ingress in uncracked concrete. However, multiple fine cracks will be encountered under service load when using SHCC. To account for their influence on chloride ingress the following empirical formula was proposed by Rokugo et al. (2007):

\[
D_a = D_0 + D_n \log(\varepsilon \omega) \tag{5}
\]

where \( D_0 \) = design value of chloride diffusivity, \( D_n \) = material constant, \( D_0 \) = constant representing the contribution of cracks and tensile strain on the chloride diffusivity of SHC, \( \varepsilon \) = tensile strain and \( \omega \) = characteristic value of maximum crack width.

Equation 5 is not defined for crack-free SHCC and the material constant \( D_0 \) is not equivalent to the diffusion coefficient of the crack-free material. For these reasons Equation 5 was not used for the new model. Instead, Equation 4 is being used with a diffusion coefficient \( D_a \) according to Equation 6:

\[
D_{0,\text{Eq.}4} = D_{0,\text{Eq.}3} = k_e k_i k_{cr} D_{\text{SHCC}}^{D_0,\text{ex.0}} \tag{6}
\]

where \( D_{\text{SHCC}}^{D_0,\text{ex.0}} \) = the diffusion coefficient determined experimentally for uncracked SHCC at \( t = t_0 \) and with a damage factor \( k_{cr} \) to account for the influence of cracks on the diffusion coefficient.

5 FUZZY-PROBABILISTIC MODEL FOR CHLORIDE INGRESS IN SHCC

5.1 Fuzzy-probabilistic model for chloride ingress

Using the fuzzy probability theory outlined in Chapter 3, and denoting fuzzy or fuzzy-stochastic variables with a tilde, Equation 2 becomes

\[
\tilde{C}_{\text{SHCC}}(x, t) = \tilde{C}_{sa} \text{ erf} \left( \frac{x}{2\sqrt{D_0 \text{SHCC} t}} \right) \tag{7}
\]
where the fuzzy-random apparent diffusion coefficient is calculated according to Equations 4 and 6 with the random parameters being replaced by the corresponding fuzzy-random ones.

5.2 Example

As outlined before, fuzzy-probability theory allows a quantification of the parameters in Equation 7 based on the available experimental data for SHCC and expert knowledge. In the following this is shown exemplarily for the chloride profiles in the SHCC specimens investigated by Sahmaran et al. (2007) if they were exposed to the experimental conditions for up to 100 years. It should be noted that the values in Table 2 have been defined only to demonstrate the possibilities of the model and do not represent a reliable parameter quantification.

Sahmaran et al. (2007) reported the experimental diffusion coefficient for the crack-free material as given in Equation 8:

\[
D_{ex,uncr,0}^{SHCC} = k_e D_{ex,0}^{SHCC} = 6.75 \times 10^{-12} \text{ m}^2/\text{s} \tag{8}
\]

This mean value is based on the results for only two specimens, which is not enough to confidently define it as a crisp parameter. Thus a triangular membership function \(\mu(D)\) was defined with a membership degree \(\mu(D) = 1.0\) for the value published by Sahmaran et al. (2007). To estimate the upper and lower boundaries of the membership function, the reported regression line for the diffusion coefficient as a function of the number of cracks was used.

For crack-free SHCC this function defined the upper boundary at \(7.75 \times 10^{-12} \text{ m}^2/\text{s}\). The lower boundary was defined to have the same distance from the peak of the triangular function, yielding a value of \(5.75 \times 10^{-12} \text{ m}^2/\text{s}\).

Chloride profiling methods are highly unreliable for exposure times of less than one year, with small measurement inaccuracies having a significant impact on the diffusion coefficient (DuraCrete 2000a). As Sahmaran et al. (2007) investigated the chloride profile after only 30 and 90 days respectively, it is expected that the standard deviation is significantly higher than the one reported in the DuraCrete project (2000c) for ordinary concrete.

The membership function of the standard deviation was defined based on reported values for the coefficient of variation CoV defined as \(CoV = (\text{standard deviation}/\text{mean value})\). It is improbable that the CoV for the diffusion coefficient in SHCC will be lower than the ones reported by Gehlen (2000) and in the DuraCrete project (2000a) for ordinary concrete. In both cases the Rapid Chloride Migration Test was used, which according to DuraCrete (2000a) is deemed to be more reliable than short-term immersion tests. Thus it is reasonable to define the lower boundary of the membership function as \(\mu_{(CoV=0.2)} = 0\), a little higher than the mean value of the coefficients of variation given in the above publications.

In the DuraCrete model (2000c) a conservative assumption of \(CoV_{90\%} = 0.285\) for design purposes is recommended due to the limited available data. In the absence of further information the peak of the membership function has thus been defined as \(\mu_{(CoV=0.285)} = 1\) and the upper boundary has been estimated conservatively as \(\mu_{(CoV=0.57)} = 0\).

The age factor \(n\) was determined similarly. As well-controlled experimental conditions were

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
<th>Type of uncertainty</th>
<th>Distribution</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{D}_{ex,uncr}^{SHCC})</td>
<td>[m²/s × 10⁻¹²]</td>
<td>Fuzzy random</td>
<td>Normal distribution</td>
<td>5.75 6.75 7.75</td>
<td>1.35 1.92 3.85</td>
</tr>
<tr>
<td>(\tilde{D}_{ex,cr}^{SHCC})</td>
<td>[m²/s × 10⁻¹²]</td>
<td>Fuzzy random</td>
<td>Normal distribution</td>
<td>56.22 57.22 58.22</td>
<td>11.2 16.0 30.0</td>
</tr>
<tr>
<td>(\tilde{n}_{uncr})</td>
<td>[-]</td>
<td>Fuzzy random</td>
<td>Beta, a = 0, b = 1</td>
<td>0.65 0.69 0.80</td>
<td>0.05 0.06 0.07</td>
</tr>
<tr>
<td>(\tilde{n}_{cr})</td>
<td>[-]</td>
<td>Fuzzy random</td>
<td>Beta, a = 0, b = 1</td>
<td>0.69 0.75 0.85</td>
<td>0.05 0.06 0.07</td>
</tr>
<tr>
<td>(k_e)</td>
<td>[-]</td>
<td>Fuzzy</td>
<td>–</td>
<td>0.58 0.68 0.75</td>
<td>– – –</td>
</tr>
<tr>
<td>(\tilde{C}_{sa})</td>
<td>[wt.-% binder]</td>
<td>Crisp</td>
<td>–</td>
<td>– 1.44 –</td>
<td>– – –</td>
</tr>
<tr>
<td>(k_e)</td>
<td>[-]</td>
<td>Crisp</td>
<td>–</td>
<td>– 1 –</td>
<td>– – –</td>
</tr>
<tr>
<td>(k_c)</td>
<td>[-]</td>
<td>Crisp</td>
<td>–</td>
<td>– 1 –</td>
<td>– – –</td>
</tr>
</tbody>
</table>

\(\tilde{D}_{ex,uncr,0}^{SHCC} = \tilde{k}_e \times \tilde{D}_{ex,0}^{SHCC}\) * For \(b = c\) the membership function in Figure 1 is triangular.
modelled, the chloride surface concentration \( C_{\text{sa}} \) and the parameters \( \hat{k} \) and \( \hat{k}_c \) were defined as crisp values. The test method factor \( \hat{k}_c \) was defined as a purely fuzzy variable as insufficient information for a fuzzy-probabilistic definition was available.

5.3 Results

Based on a fuzzy-probabilistic analysis of Equation 7 with the parameters given in Table 2, the chloride profiles in Figures 5 to 7 were obtained. When interpreting these figures, the preliminary nature of the parameter quantification should be considered. Nonetheless, some first tendencies can be observed.

Figure 5 shows that while cracking influences the transport of chlorides into SHCC significantly less than it does in mortar or concrete, cracks still have a profound impact on the chloride profiles. The influence of time on uncertainty can be seen in Figure 6 where the non-stochastic uncertainty for the mean value of the chloride profile after one and 100 years is shown. As can be seen in Figure 7 the non-stochastic uncertainty for quantiles relevant for design is much more significant than for the mean value. This highlights the importance of a thorough definition of the membership function for fuzzy or fuzzy-stochastic parameters.

6 CONCLUSION

In recent years it has been recognised that ensuring concrete durability is a significant challenge. This challenge has been addressed by developing performance-based durability design models for ordinary concrete, which allow the full utilisation of the material. However, these models cannot be used for new cement-based composites such as SHCC due to a lack of available data.

As presented in this paper, fuzzy-probability theory is a practical and transparent tool that allows the quantification of model parameters based on limited data and expert knowledge and thus the development of a performance-based durability design model for SHCC. The application of fuzzy-probability theory is not limited to SHCC, however, but may also facilitate the modelling of the resistance of ordinary concrete to various exposures. It may also help to model the effect of cracks in concrete on its durability, which is not covered by existing models.

While the potential of the presented approach is obvious, a significant effort is still required to reliably quantify the parameters of the proposed ingress model and to further develop it into a service life design model for SHCC. To this end long-term immersion tests on cracked and crack-free SHCC specimens are
being planned. Together with an extensive literature review the generated data will facilitate a reliable parameter quantification.

REFERENCES


NT Build 492 1999. Concrete, mortar and cement based repair materials: Chloride migration coefficient from non-steady state migration experiments.


