INVITED LECTURE
DURABILITY BASED LIFE CYCLE ASSESSMENT OF CONCRETE WITH SUPPLEMENTARY CEMENTITIOUS MATERIALS EXPOSED TO CARBONATION

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Abstract
Until now, it remains unclear how ‘green’ concrete compositions with high volumes of supplementary cementitious materials really are, especially when subject to carbonation-induced steel corrosion. This paper presents results from accelerated carbonation tests for high-volume fly ash (HVFA) and fly ash + silica fume (FA+SF) concrete. They served as input for a probabilistic service life prediction based on fib Bulletin 34, and a subsequent life cycle assessment. The inverse effective carbonation resistance of the two concrete types was compared with the one of traditional concrete that is normally used in outdoor, sheltered environments. An attempt was also made to determine the model input parameter that accounts for concrete’s curing behaviour using literature data. Other input parameters related to meteorological conditions were accounted for with weather station information. In the end, it was found that the estimated time to carbonation-induced steel depassivation for the less carbonation resistant HVFA and FA+SF concrete still exceeds a predefined life span of 100 years by far. As a consequence, global warming potentials (GWPs) calculated for the required concrete volume per unit of strength and service life indicate that an important reduction in greenhouse gas emissions is possible for both concrete types (GWP -29 to -44%).

1. INTRODUCTION
Within a life cycle assessment (LCA) of concrete containing supplementary cementitious materials (SCMs), the selected functional unit (FU) should include all relevant concrete properties, such as strength and durability, to assess the overall environmental impact in a proper way. Depending on the type and the amount of SCM, its addition to the concrete mix may reduce or increase the strength, which will affect the dimensions of structural elements needed to carry a specified load. With relation to durability, the specific environmental conditions determine the expected number of rehabilitation actions in time. Both issues can result in less or more concrete manufacturing and thus less or more environmental impact [1]. In this paper, these effects have been studied while using a combined service life design
(SLD) – LCA approach for concrete with fly ash (and silica fume) in a carbonation exposed environment (exposure class XC3: a sheltered outdoor environment). The carbonation resistance of a concrete composition basically depends on two aspects, i.e. its susceptibility to diffusion of CO₂ and the amount of carbonatable matter available. If cured well, concrete with fly ash can feature a low permeability, which will hinder the CO₂ ingress. On the other hand, the amount of portlandite is reduced because of the pozzolanic reaction, reducing the buffering capacity versus CO₂ [2]. Accelerated carbonation tests provide the input for a probabilistic service life prediction based on the fib model code for service life design (fib Bulletin 34) [3]. With full notion of the materials’ strength and service life a LCA with a specific focus on the global warming potential (GWP) was finally carried out in SimaPro.

2. MATERIALS AND METHODS

2.1 Concrete mixtures

In total, three concrete mixtures were manufactured (Table 1). Mixture T(0.55) is an Ordinary Portland Cement (OPC) concrete composition with a minimum cement content and a maximum water-to-cement (W/C) ratio conforming to NBN B15-001 for exposure class XC3, a moderately humid environment with exposure to carbonation-induced steel corrosion. A common example of such an environment is exterior concrete sheltered from rain.

Table 1: Concrete mixture proportions

<table>
<thead>
<tr>
<th></th>
<th>T(0.55)</th>
<th>F50</th>
<th>F40SF10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (kg/m³)</td>
<td>715</td>
<td>645</td>
<td>791</td>
</tr>
<tr>
<td>Gravel (kg/m³)</td>
<td>1188</td>
<td>1071</td>
<td>1141</td>
</tr>
<tr>
<td>CEM I 52.5 N (kg/m³)</td>
<td>300</td>
<td>225</td>
<td>170</td>
</tr>
<tr>
<td>Fly ash (FA) (kg/m³)</td>
<td>0</td>
<td>225</td>
<td>136</td>
</tr>
<tr>
<td>Silica fume (SF) (kg/m³)</td>
<td>0</td>
<td>0</td>
<td>34</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>165</td>
<td>157.5</td>
<td>119</td>
</tr>
<tr>
<td>Superplasticizer (ml/kg B)</td>
<td>2</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>W/B</td>
<td>0.55</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>FA/B</td>
<td>0</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>SF/B</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Slump*</td>
<td>S4</td>
<td>S5</td>
<td>S4</td>
</tr>
<tr>
<td>Strength class**</td>
<td>C30/37</td>
<td>C40/50</td>
<td>C50/60</td>
</tr>
</tbody>
</table>

* S1 (10-40 mm), S2 (50-90 mm), S3 (100-150 mm), S4 (160-210), S5 (≥ 220 mm)
** based on the 5% characteristic (compressive strength) value cf. EN 1990 (n = 3, V₀; unknown)

Within the other two concrete compositions 50% of the total binder (B) content consisted of SCMs. Mixture F50 counts as a HVFA concrete since half of the total binder content consisted of pozzolanic FA. To compensate for the rather slow hydration reaction of the FA, a higher total binder content of 450 kg/m² and lower water-to-binder (W/B) ratio (0.35) were applied. As such, quite a high early age strength performance could still be achieved. The strength class of the material (= C40/50), which is based on the 28-day characteristic compressive strength, proves this. To improve the early age strength performance without increasing the total binder content too much, SF could be introduced as third powder in the
binder system. This was done for composition F40SF10 in which the total binder content consisted for 50% of Portland cement, 40% of FA and 10% of SF. With a total binder content of only 340 kg/m³, a strength class of no less than C50/60 could be achieved.

2.1 Carbonation testing

After 21 days of optimal curing at 20°C and 95% RH, 5 of the 6 surfaces of 9 cubic specimens (side: 100 mm) per mixture were treated with an impermeable coating to ensure a unidirectional flow of CO₂ during an accelerated carbonation experiment. The untreated side was always a cast surface of the cube. After applying the coating, the specimens were stored again under optimal curing conditions until they were 28 days of age. Then, the cubes of mixtures T(0.55), F50 and F40SF10 were stored in carbonation chamber conditioned at 1% CO₂, 20°C and 60% RH. Every four weeks, three cubes per test series were taken out of the chamber and split. After spraying the 1% phenolphthalein solution onto the fractured surfaces, the carbonated area showed colourless, while the non-carbonated area coloured purple. For each concrete mixture tested, the measured carbonation depths \( x \) (in mm) were plotted as a function of the square root of the exposure time \( t \) (in weeks) to determine an experimental (accelerated) carbonation coefficient \( A_{\%} \) (in mm/√weeks). Because the \( fib \) Bulletin 34 model for carbonation-induced corrosion uses data from a carbonation experiment at 2% CO₂ [3], our data still needed to be converted in order to be representative for the latter CO₂ concentration. Therefore, the formula proposed by Sisomphon and Franke [4] was used (Equation 1). It allows for converting carbonation coefficients obtained at a certain CO₂ concentration to a carbonation coefficient representing another concentration. The formula is believed to be valid for CO₂ concentrations up to 3% [4].

\[
\frac{A_{2\%}}{A_{1\%}} = \sqrt{\frac{c_{2\%}}{c_{1\%}}}
\]  

3. SERVICE LIFE PREDICTION

3.1 Limit state function for carbonation-induced depassivation

The \( fib \) Bulletin 34 provides the following concrete and environment specific limit state function (Equation 2) for carbonation-induced steel depassivation [3].

\[
g(a, x_c(t)) = a - x_c(t) = a - \sqrt{2 \cdot k_e \cdot k_c \cdot R_{\text{NAC,0}}^{-1} \cdot C_S \cdot \sqrt{t} \cdot W(t)}
\]

with \( a \), the concrete cover (mm), \( x_c(t) \), the carbonation depth at time \( t \) (mm), \( k_e \), the environmental function for the relative humidity in practice (–), \( k_c \), the execution transfer parameter with respect to concrete curing (–), \( R_{\text{NAC,0}}^{-1} \), the inverse effective carbonation resistance under natural carbonation conditions ((mm²/years)/(kg/m³)), \( C_S \), the atmospheric CO₂ concentration (kg/m³) and \( W(t) \), the weather function (–).

3.2 Inverse effective carbonation resistance

The value for \( R_{\text{NAC,0}}^{-1} \) is normally calculated from the effective inverse carbonation resistance of dry concrete \( R_{\text{ACC,0}}^{-1} \), determined at a certain point in time \( t_0 \) using the accelerated carbonation test prescribed by \( fib \) Bulletin 34 (Equation 3) [3].
\[ R_{\text{NAC},0}^{-1} = k_t \cdot R_{\text{ACC},0}^{-1} + \varepsilon_t \]  

(3)

with \( k_t \), a normal distributed regression parameter (1.25 ± 0.35) which considers the influence of the test method (–) and \( \varepsilon_t \), a normal distributed error term (315.5 ± 48) which takes into account inaccuracies related to the accelerated test ((mm²/years)/(kg/m³)). \( R_{\text{ACC},0}^{-1} \) was estimated from the accelerated carbonation experiment described in Section 2.1. Once the theoretical carbonation coefficient for 2% CO₂ was obtained by means of Equation 1, the well-known square-root-time law was applied again to calculate the theoretical carbonation depth \( d_c \) (m) after 28 days of exposure in an atmosphere containing 2% CO₂. From this value, \( R_{\text{ACC},0}^{-1} \) in m²/s/kgCO₂/m³ can be calculated (Equation 4). The same formula is used in the DuraCrete model [5], which is the predecessor of fib Bulletin 34 [3].

\[ R_{\text{ACC},0}^{-1} = \left( \frac{d_c}{419.45} \right)^2 \]  

(4)

### 3.3 Concrete cover

NBN EN 1992-1-1 prescribes a minimum concrete cover (a) of 35 mm for construction class S6 which corresponds with a design service life of 100 years in exposure class XC3. Although strictly specified, the actual value of this cover varies due to the unavoidable inaccuracies that occur in the construction stage. Therefore, this parameter has to be considered as a stochastic variable. As such, a standard deviation of 8 mm on the minimum cover was taken into consideration. It is seen as appropriate for concrete without particular execution requirements [3]. The probabilistic distribution was considered lognormal.

### 3.4 The environmental function

Environmental function \( k_e \) (Equation 5) takes into account that the humidity level (RH\(_{\text{real}}\)) of the actual concrete environment may differ from the reference relative humidity (RH\(_{\text{ref}}\): 60%) imposed during the accelerated carbonation test.

\[ k_e = \left( \frac{1 - \left( \frac{\text{RH}_{\text{real}}}{100} \right)^{f_e}}{1 - \left( \frac{\text{RH}_{\text{ref}}}{100} \right)^{g_e}} \right)^{g_e} \]  

(5)

where \( f_e \) (= 5.0) and \( g_e \) (= 2.5) represent two constant parameters which are independent of the exposure conditions and management phases. Data for RH\(_{\text{real}}\) are normally collected from a weather station close to the location of the concrete structure. Since the main purpose of this research is an environmental evaluation of the newly developed HVFA and FA+SF concrete compositions which have not been applied yet in practice, a fictional concrete structure assumed to be located near the weather station of Zaventem, Belgium was considered. The daily mean values recorded at this weather station between 1999 and 2008 were provided by the Royal Meteorological Institute (KMI). They were used to estimate the (Beta) distribution for RH\(_{\text{real}}\) (79 ± 9%, lower boundary: 40%, upper boundary: 100%).
3.5 The execution transfer parameter

A value for the execution transfer parameter $k_c$ (–) that accounts for the curing effect is obtained from Equation 6.

$$k_c = \left(\frac{t_c}{T}\right)^{b_c}$$  \hspace{1cm} (6)

with $b_c$, the exponent of regression (–) and $t_c$, the period of curing (days). According to fib Bulletin 34 [3], any measures taken to prevent premature desiccation of the concrete surface (water curing, air curing while covering the concrete surface with sheets, etc.) are seen as ways that guarantee proper curing. In this research, the curing period corresponded with the period during which the samples were stored at 20 °C and 95% RH, which was 28 days.

Surprisingly, fib Bulletin 34 specifies only one possible input for the value of $b_c$ (normal distribution, mean: $-0.576 \pm 0.024$) [3], while the curing behaviour of different concrete types can be very different. The rather slow pozzolanic FA reaction taking place in the HVFA and FA+SF concrete may require longer curing than more traditional concrete in order to achieve the highest carbonation resistance possible. Unfortunately, no carbonation tests have been performed at different curing ages to find mix specific values for $b_c$ per concrete type. To cope with this issue, an attempt was made to estimate $b_c$ for concrete compositions with a varying FA content and W/B ratio by using carbonation data from literature. For instance, Burden performed carbonation tests on concrete with 0%, 30%, 40% and 50% of the cement replaced with FA [6]. Per FA content, three different W/B ratios were considered, i.e. 0.34, 0.40 and 0.50. Five different curing periods, i.e. 1, 3, 7, 14 and 28 days, were chosen. This curing consisted of immersion in lime water. Afterwards, the concrete was exposed to 1% CO₂ at 23°C and 65% RH for 90 days. Table 2 gives an overview of the different concrete compositions tested and the carbonation depths measured after 90 days of exposure.

Table 2: Measured carbonation depths for the concrete mixtures tested by Burden [6]

<table>
<thead>
<tr>
<th>Mix</th>
<th>Binder content (kg/m³)</th>
<th>FA content (%)</th>
<th>W/B (–)</th>
<th>tₖ: 1 d</th>
<th>tₖ: 3 d</th>
<th>tₖ: 7 d</th>
<th>tₖ: 14 d</th>
<th>tₖ: 28 d</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0 34</td>
<td>340</td>
<td>0</td>
<td>0.34</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F0 40</td>
<td>400</td>
<td>0</td>
<td>0.34</td>
<td>5</td>
<td>3.5</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>F0 50</td>
<td>465</td>
<td>30</td>
<td>0.34</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>F30 34</td>
<td>340</td>
<td>30</td>
<td>0.40</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>F30 40</td>
<td>400</td>
<td>30</td>
<td>0.40</td>
<td>9</td>
<td>7</td>
<td>4.5</td>
<td>3.5</td>
<td>3</td>
</tr>
<tr>
<td>F30 50</td>
<td>450</td>
<td>30</td>
<td>0.50</td>
<td>12</td>
<td>9</td>
<td>6</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td>F40 34</td>
<td>340</td>
<td>40</td>
<td>0.34</td>
<td>9</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>F40 40</td>
<td>400</td>
<td>40</td>
<td>0.40</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>F40 50</td>
<td>450</td>
<td>40</td>
<td>0.50</td>
<td>12</td>
<td>9</td>
<td>6</td>
<td>5.5</td>
<td>5</td>
</tr>
<tr>
<td>F50 34</td>
<td>340</td>
<td>50</td>
<td>0.34</td>
<td>12</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>F50 40</td>
<td>400</td>
<td>50</td>
<td>0.40</td>
<td>11</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>F50 50</td>
<td>450</td>
<td>50</td>
<td>0.50</td>
<td>16</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

It must be said that the carbonation test results obtained in Burden [6] only allow for assessing the effect of the W/B ratio and the FA content. To determine a proper $b_c$ value for
composition F40SF10, one should also have an idea on what the effect of SF is. In Sulapha et al. [7], the evolution of the carbonation coefficient was studied for concrete mixtures with a binder system consisting of 100% OPC (N50), 70% OPC and 30% FA (FA30), and 90% OPC and 10% SF (SF10), and this for a fixed total binder content (340 kg/m³) and W/B ratio (0.50). The carbonation coefficients (in mm/√weeks) resulted from an accelerated carbonation test during which the concrete was exposed to 6.5% CO₂ at 30°C and 65% RH for 48 weeks. In total, four different curing periods in lime-saturated water were considered, i.e. 1, 3, 7 and 28 days. Table 3 gives the mixture details and the test results cf. Sulapha et al. [7].

Table 3: Measured carbonation depths for the concrete mixtures tested by Sulapha et al. [7]

<table>
<thead>
<tr>
<th>Mix</th>
<th>Binder content (kg/m³)</th>
<th>Binder composition</th>
<th>W/B (-)</th>
<th>Carbonation depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>t_c: 1 d</td>
</tr>
<tr>
<td>N50</td>
<td>350</td>
<td>100% OPC</td>
<td>0.50</td>
<td>38</td>
</tr>
<tr>
<td>FA30</td>
<td>350</td>
<td>70% OPC + 30% FA</td>
<td>0.50</td>
<td>46</td>
</tr>
<tr>
<td>SF10</td>
<td>350</td>
<td>90% OPC + 10% SF</td>
<td>0.50</td>
<td>48</td>
</tr>
</tbody>
</table>

In *fib* Bulletin 34 [3], a Bayesian regression procedure is mentioned for the quantification of b_c based on experimental data. It therefore refers to DARTS R2.16 [8] and Gehlen [9]. With carbonation depths for different curing periods available, one needs to fill out the following Equation 7 for each curing period i.

$$k_{ci} = \left(\frac{x_{c,i}(t)}{x_{c,7}(t)}\right)^2$$

with $k_{ci}$, the curing factor (–), $x_{c,i}(t)$, the final carbonation depth (mm), and $x_{c,7}(t)$, the final carbonation depth (mm) after 7 days of optimal curing, the reference curing period. Time t equals 90 days cf. Burden [6] or 48 weeks cf. Sulapha et al. [7], the total exposure periods. As such, values for $k_{ci}$ are obtained which can be plotted as a function of the curing period $t_c$. The value of parameter $b_c$ can then be determined by fitting Equation 8 to these data points.

$$b_c = a_c \cdot t_c^{b_i}$$

In fact, this general equation contains still another parameter of regression besides $b_c$. However, according to Gehlen [9] this parameter $a_c$ is to be set equal to $7^{b_c}$, so $b_c$ is actually the only output of the regression analysis.

3.6 The atmospheric CO₂ concentration

$C_S$ corresponds with the expected increased atmospheric CO₂ level with time without additional emissions attributed to motorized traffic (kg/m³). The *fib* Bulletin 34 [3] assumes a normal distributed value of $0.00082 \pm 0.0001$ kg/m³ to take into account that the current value will still increase with time (due to the greenhouse effect). According to Ehrenberg and Geiseler [10] an increase of about 1.5 ppm per year can be expected.

3.7 The weather function

By means of weather function $W(t)$ (Equation 9) the effect of occurring wetting events such as (driving) rain is included in the limit state function.
\[ W(t) = \left( \frac{t_0}{t} \right)^{(p_{SR} \cdot \text{ToW})^{b_w}} \]  

(9)

with \( t_0 \), the time of reference (= 0.0767 years), \( p_{SR} \), the probability of driving rain (–), \( \text{ToW} \), the time of wetness (–) and \( b_w \), the normal distributed exponent of regression (0.446 ± 0.163). For exposure class XC3, the concrete is assumed to be sheltered from rain. Logically, \( W(t) \) is to be omitted then. Nevertheless, to know what its effect for unsheltered concrete would be, proper \( p_{SR} (= 0.16) \) and \( \text{ToW} (= 0.31) \) values were once estimated from the earlier mentioned KMI weather station data.

### 3.8 Calculation approach

The reliability indices (\( \beta \)) and probabilities of failure (\( P_f \)) associated with Equation 2 were calculated using the First Order Reliability Method (FORM) available in the probabilistic Comrel software. In compliance with fib Bulletin 34 [3], they need to meet the requirements for the depassivation limit state (\( \beta \geq 1.3 \) and \( P_f \leq 0.10 \)) to qualify for use.

### 4. LIFE CYCLE ASSESSMENT

#### 4.1 Definition of goal and scope

This LCA was conducted to quantify the theoretical reduction in greenhouse gas emissions that could be achieved by using the proposed HVFA and FA+SF concrete instead of traditional OPC concrete. To do this correctly, the LCA study should take into account differences in strength and durability between the concrete types. Therefore, the required concrete volume per unit of strength and service life was chosen as FU. This was done by dividing the 1 m³ concrete volume by the minimum characteristic cube strength as indicated by the second number in the strength class name (Table 1) and the service life estimated (Table 5). The maximum service life taken into account in the calculation of this FU was 100 years, the prescribed service life of important concrete structures, such as bridges, etc.

#### 4.2 Inventory analysis

Per concrete constituent, the necessary inventory data were collected from the Ecoinvent database [11]. Their proper short descriptions as mentioned in the database are given below.

- Sand: ‘Sand, at mine/CH U’
- Gravel: ‘Gravel, round, at mine/CH U’
- CEM I 52.5 N: ‘Portland cement, strength class Z 52.5, at plant/CH U’
- FA: ‘Electricity, hard coal, at power plant/BE U’, partially by economic allocation
- SF: ‘MG-silicon, at plant/NO U’, partially by economic allocation

For the allocation of impacts attributed to FA and SF, the economic allocation coefficients as proposed by Chen et al. [12] and Chen [13] were applied. For the former by-product, this is 1.0% of the impact of the coal fired electricity production. For the latter this is 4.8% of the impact of silicon metal production corresponding with the production of 1 kg SF.

Superplasticizer (SP) inventory data were obtained from an environmental declaration published by the EFCA [14]. The transport of each constituent to the concrete plant was not incorporated in the LCA since its environmental impact is always very case specific. The impacts related with the production process at a concrete plant were included by the partial
assignment of the following life cycle inventory (LCI) from EcoInvent to each concrete mix: ‘Concrete, normal at plant/CH U’. It comprises the whole process of producing 1 m³ of ready-mixed concrete, including all internal processes and infrastructure, and this for a traditional concrete which is also accounted for in the LCI. By removing the original concrete constituents and their transport from this inventory, a new LCI is obtained that simply represents the concrete production in general, without any link with a predefined concrete composition. This new LCI was assigned to each of the three studied concrete mixtures.

4.3 Impact analysis and interpretation

The IPCC 2013 GWP 100a impact method was used to calculate the GWP (kg CO₂ eq) for a timeframe of 100 years. All calculations were done in the LCA software SimaPro 8.

5. RESULTS AND DISCUSSION

5.1 Inverse effective carbonation resistance

When looking at R_{ACC,0}^{-1} for evaluation of concrete’s susceptibility to carbonation, the preference obviously goes to lower values. The HVFA and FA+SF concrete are clearly less carbonation resistant than the OPC reference (Table 4). This is not an unexpected result. Concrete in which large portions of the cement have been replaced with FA (and SF), carbonates faster as less Portland clinker is present which produces portlandite upon hydration, and the pozzolanic reactions consume portlandite which causes a reduced buffering capacity versus CO₂. For a quantitative evaluation of the portlandite consumption during hydration, all or not in combination with exposure to increased CO₂ levels, we refer to Van den Heede [1]. The trends observed in that study by means of thermogravimetric analysis confirmed the differences in carbonation resistance between the three compositions.

Note that applying a lower W/B ratio (from 0.55 to 0.35) to lower concrete’s permeability to CO₂ cannot sufficiently compensate for the reduced CO₂ buffering capacity effect. The incorporation of 10% SF in mix FA40SF10 on the other hand seems to have been beneficial for the concrete’s carbonation resistance. Although FA+SF composition F40SF10 still performs less well in comparison with OPC reference T(0.55), an important improvement is clear when making the comparison with HVFA concrete F50. The inverse effective carbonation resistance of F40SF10 is only a little more than half of the R_{ACC,0.5} value of F50. This phenomenon is mainly attributed to the filler effect of the SF at young age which results in a denser microstructure and thus a hindered CO₂ penetration.

Table 4: Inverse effective carbonation resistance of the tested concrete mixtures.

<table>
<thead>
<tr>
<th>R_{ACC,0}^{-1} ((mm²/years)/(kg/m³))</th>
<th>T(0.55)</th>
<th>F50</th>
<th>F40SF10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± stdv.</td>
<td>2684 ± 303</td>
<td>11292 ± 343</td>
<td>5835 ± 165</td>
</tr>
</tbody>
</table>

5.2 Estimation of the execution transfer parameter

Regression parameter bₜ significantly increases with an increasing FA content (Figure 1). This trend is observed for all studied W/B ratios. On the other hand, it cannot simply be assumed that the value of bₜ is proportional to the W/B ratio. For a given FA content, bₜ increases in a pronounced way from a W/B ratio of 0.34 to a W/B ratio of 0.40. However, this increase does not progress for higher W/B ratios of e.g. 0.50. On the contrary, for FA replacement levels of 40% and 50%, the value of bₜ tends to decrease again.
Figure 2 gives an impression on how the type of SCM (FA or SF) affects the value of $b_c$. When based on the experimental data obtained by Sulapha et al. [7], it seems that the incorporation of 30% FA increases the value of $b_c$ significantly. This finding is in agreement with the calculations done for the Burden data [6]. Nevertheless, for total binder contents (340-350 kg/m³) and W/B ratios (0.50) that were actually quite similar, the values of $b_c$ differed quite a bit (F30_50: -0.726 versus FA30: -0.435). The same goes in fact for the OPC concrete (F0_50: -0.950 versus N50: -0.610). The reason for these differences remains for the moment unclear. However, one must keep in mind that the carbonation tests done by Burden [6] and Sulapha et al. [7] were not the same in applied CO₂ concentration (1% versus 6.5% CO₂) and total exposure time (90 days versus 48 weeks). This obviously makes adequate comparison difficult. For instance, in Van den Heede [1] it was found that increasing the CO₂ concentration too much (e.g. to 10% CO₂), may lead to important underestimations of the carbonation coefficients that are expected at lower, realistic concentrations after applying a conversion formula. Similar effects could play a role at 6.5% CO₂ cf. Sulapha et al. [7].

Figure 1: Regression parameter $b_c$ estimated from data by Burden [6]

Figure 2: Regression parameter $b_c$ estimated from data by Sulapha et al. [7]

The presence of 10% SF in the concrete (SF10) also seems to increase the value of $b_c$, be it not to the same extent as the incorporation of 30% FA (SF10: -0.513 versus N50: -0.435, Sulapha et al. [7]). Preferably, it would have been good to see how the incorporation of both
FA and SF affect the value of regression parameter $b_c$. However, no such experimental carbonation data could be found in the literature until now.

From the $b_c$ values that have been fitted until now using literature data, one could assign preliminary values to the concrete mixtures that have been considered in this research. For HVFA mixture F50 this is rather easy because the FA content (50%), the W/B ratio (0.35) and the total binder content (450 kg/m³) are almost identical to those of HVFA mixture F50_34 tested by Burden [6] (see Table 2). For OPC reference T(0.55) this is less straightforward because Burden [6] does not provide carbonation data for concrete with the same total binder content (300 kg/m³) and W/B ratio (0.55). For now, it was decided to use the estimated $b_c$ value (Figure 1: $-0.950 \pm 0.040$) of mixture F0_50 as preliminary input to the prediction model despite the higher binder content (340 kg/m³) and the lower W/B ratio (0.50) of the mixture. The $b_c$ values obtained for the N50 composition of Sulpha et al. [7] were also used once as input. Probably, a lower binder content (300 kg/m³) and a higher W/B ratio (0.55) will result in even higher values of $b_c$. However, since this trend could not be verified with actual data, no higher values were considered as input for now. For composition F40SF10 containing both 40% FA and 10% SF, it is even more difficult to estimate the proper regression parameter $b_c$ based on the limited information available from literature. Since the data of Sulpha et al. indicated that the presence of 10% SF also increases the value of $b_c$ substantially for a given binder content and W/B ratio, it would be wrong to just focus on the concrete’s FA content. In other words, based on the currently available information, it would be better not to work with the $b_c$ value for concrete containing 40% FA and use the $b_c$ value concrete with a 50% cement replacement level instead. Thus, the $b_c$ value of F50_34 ($-0.897\pm0.010$) was used just like for the HVFA composition. Evidently, the value of $b_c$ should be updated as soon as more data specifically for the FA+SF concrete become available.

5.3 Time to carbonation-induced steel depassivation

Equation 2 was first considered with exclusion of the parameters $k_e$, $k_c$ and $W(t)$. As such, the time to depassivation for compositions T(0.55), F50 and F40SF10 amounts to 96 years, 24 years and 46 years, respectively (Table 5). Knowing this, the OPC reference will be preferred over compositions F40SF10 and F50, in that particular order.

Table 5: Time to carbonation-induced steel depassivation of the tested concrete mixtures.

<table>
<thead>
<tr>
<th>Depassivation period (years)</th>
<th>T(0.55)</th>
<th>F50</th>
<th>F40SF10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eq. 2 excl. $k_e$, $k_c$ and $W(t)$</td>
<td>96</td>
<td>24</td>
<td>46</td>
</tr>
<tr>
<td>Eq. 2 excl. $k_c$ and $W(t)$</td>
<td>153</td>
<td>39</td>
<td>74</td>
</tr>
<tr>
<td>Eq. 2 excl. $k_e$ and $W(t)$</td>
<td>$358/224^{**}$</td>
<td>85</td>
<td>162</td>
</tr>
<tr>
<td>Eq. 2 excl. $k_e$ and $k_c$</td>
<td>508</td>
<td>99</td>
<td>214</td>
</tr>
<tr>
<td>Eq. 2 excl. $W(t)$</td>
<td>$572/357^{**}$</td>
<td>135</td>
<td>342</td>
</tr>
</tbody>
</table>

$b_c$ estimated from the carbonation data by *Burden [6], **Sulpha et al. [7]

Inclusion of the concrete and environment related input parameters, changes the prediction outcome substantially (Table 5). To see which parameters have the largest effect, they were implemented one by one in Equation 2. All of them tend to extend the depassivation period. With implementation of $W(t)$ for an unsheltered exposure condition (which is not really the exposure class under investigation in this study), the service life extending effect is the most...
pronounced. The curing factor \( k_c \) is the second largest contributor, followed by the environmental factor \( k_e \). Note that a change in value for \( b_c \) can immediately have important consequences. This was demonstrated by using \( b_c \) values estimated from two different literature sources (Burden [6] and Sulapha et al. [7]) for the OPC concrete.

The most representative service life estimation for outdoor sheltered concrete is obtained by using the full limit state function with exclusion of \( W(t) \). This calculation approach does not lead to a change in the order of preference for the three mixtures. Only the duration of the carbonation-induced depassivation period increases substantially to values that exceed the predefined 100 years life span by far, and this for all mixtures.

Finally, be advised that the now obtained service life estimations should still be interpreted with caution. Carbonation tests have been performed on uncracked concrete while in practice it is really difficult to avoid cracking. The limit state function also does not account for the presence of cracks, which serve as direct pathways for \( \text{CO}_2 \) to the embedded steel rebars. Further research on that matter is certainly still recommended.

### 5.4 Strength and service life related global warming potential

Without consideration of the input parameters \( k_c, k_e \) and \( W(t) \), the GWP of the alternative concrete types F50 and F40SF10 does not look very appealing (Figure 3). The GWP value of the HVFA mixture is almost three times higher than the one of the OPC reference. This is mainly due to the poor service life performance (Table 5: 24 years versus 96 years) of the former concrete type. The higher strength of the composition F50 (C40/50 versus C30/37), could not compensate for this in the calculation of the proper functional unit for LCA.

![Figure 3](image-url) Global warming potential (GWP in kg CO2 eq) of the required concrete volume per unit of strength and service life

The lower \( R_{\text{ACC},0}^{-1} \) value for the FA+SF composition in comparison with the HVFA mixture (Table 4) which postponed the time to carbonation-induced depassivation substantially to 46 years (Table 5) clearly had its benefits for the overall GWP of the mixture. Moreover, its higher strength class (C50/60) resulted in an additional beneficial effect. Nevertheless, the GWP value of the OPC reference remained around 14% lower in the end. Thus, the very basic service life prediction not related to the specific properties and conditions of the concrete and its environment seems to indicate that replacing 50% of the cement by FA (and SF) is not a very sustainable practice. On the other hand, with consideration of the concrete’s curing behaviour (\( k_c \) for 28 days of optimal curing) and the high relative humidity (\( k_e \)) in the most critical exposure condition which is outdoor and sheltered, the predefined life span of 100 years is not an issue anymore for the HVFA and FA+SF concrete. As a consequence, their GWP values turn out to be 29% and 44% lower than the one of T(0.55).
6. CONCLUSIONS

- HVFA concrete is much less resistant to carbonation than the OPC reference for exposure XC3. The incorporation of 10% SF and 40% FA as cement replacement results in a significantly improved carbonation resistance. However, in comparison with the OPC reference, the carbonation performance is still unsatisfactory.

- A concrete and environment related service life prediction for HVFA and FA+SF concrete cf. *fib* Bulletin 34 still results in depassivation periods exceeding 100 years, despite their lower carbonation resistance. However, further research is needed to determine mix specific curing factors. As literature data showed that $b_c$ is definitely function of the FA and SF content as well as the W/B ratio, the current use of only one overall value for all concrete types should be abandoned.

- For the required concrete volume per unit of strength and service life, important GWP reductions seem possible with HVFA and FA+SF concrete (GWP -29 to -44%).

REFERENCES