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Example Manual

Concrete Carbonation – fib Bulletin No. 34

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Concrete carbonation according to fib Bulletin 34

1. Introduction

The complex model of concrete carbonation is based on [1] and calculates the depth of the carbonation front x_c at time t. In this example, a prediction of the carbonation depth x_c is made for a newly concreted slab bridge after a period of 10 years of operation. A concrete mix with CEM I 45.5 R with a water-to-cement ratio w/c = 0.55 was used, with a curing time of 14 days. The bridge is located in an environment with a normal CO_2 concentration (420 ppm). Based on meteorological data for the location, the average temperature of ambient air T = 12°C, relative humidity RH = 75% and 55 rainy days per year were measured at the time of the construction of the bridge.

2. Input variables

Notation	Variable	Value	Unit
t	Time of exposure	10	years
C_{CO2}	CO_2 content in the atmosphere	789.83	mg/m^3
RH	Relative humidity	75.00	%
b_c	Exponent of regression of execution transfer parameter function	–0.567	-
t_c	Curing period	14	days
R_{ACC}^{-1}	Inverse effective carbonation resistance of dry concrete from ACC-test	$9.80\cdot10^{-11}$	(m^2/s)/(kg/m^3)
k_t	Regression parameter of inverse effective carbonation resistance function	1.25	-
ε_t	Error term of inverse effective carbonation resistance function	$1.00\cdot10^{-11}$	(m^2/s)/(kg/m^3)
t_w	Days with rainfall more than 2.5 mm/day	55	days
p_{SR}	Probability of driving rain	1.00	-
b_w	Exponent of regression of weather function	0.446	-
Θ	Uncertainty factor of model	1.00	-

3. Deterministic Calculation and Comments

The CO_2 content on the atmosphere is set in parts per million by volume (ppm). In the model it is needed to be in mg/m^3. For the conversion following relation can be used with M_{CO2} = 44 g/mol, p = 101 325 Pa, R = 8.314 J/(mol·K) and T the temperature of structural elements or ambient air in K:

$$C_{CO2}[\mathrm{mg/m^3}] = M_{CO2}\cdot 10^3 \frac{p}{RT} C_{CO2}[\mathrm{ppm}]\cdot 10^{-6} = 44\cdot 10^3\cdot \frac{101325}{8.314\cdot(12+273.15)}\cdot 420\cdot 10^{-6} = 789.83\ \mathrm{mg/m^3}$$

For easier conversion see the 'C_CO2' sheet in the Excel template file, where the temperature in °C is defined as an input parameter and the CO_2 concentration is calculated in mg/m^3 for the range of values in ppm.

The execution transfer parameter k_c takes into account the influence of curing defined by the number of curing days t_c on effective carbonation resistance with recommended value b_c = –0.567:

$$k_c = \left(\frac{t_c}{7}\right)^{b_c} = \left(\frac{14}{7}\right)^{-0.567} = 0.675$$

The inverse effective carbonation resistance R_{ACC}^{-1} is to be determined by accelerated carbonation tests (ACC test method). If no test data is available, the literature-derived data can be used for orientation purposes; see also the 'R_ACC-1' sheet in the Excel template file. The factors k_t and ε_t have been introduced in order to transform the results gained under the accelerated carbonation conditions into an inverse carbonation resistance value under natural carbonation conditions (NAC), $R_{NAC,0}^{-1}$ with recommended values $k_t = 1.25$ and $\varepsilon_t = 1 \cdot 10^{-11}$ (m^2/s)/(kg/m^3):

$$R_{NAC,0}^{-1} = k_t \cdot R_{ACC}^{-1} + \varepsilon_t = 1.25 \cdot 9.80 \cdot 10^{-11} + 1.00 \cdot 10^{-11} = 13.25 \cdot 10^{-11}\ \frac{\mathrm{m^2/s}}{\mathrm{kg/m^3}}$$

Time of wetness is the number of rainy days t_w per year (days with rainfall more than 2.5 mm/day):

$$ToW = \frac{t_w}{365} = \frac{55}{365} = 0.151 \text{ years}$$

The environmental function k_e considers the influence of relative humidity RH on the carbonation resistance of the concrete and is calculated as (with $RH_{ref} = 65\%$):

$$k_e = \left(\frac{1-(RH/100)^5}{1-(RH_{ref}/100)^5}\right)^{2.5} = \left(\frac{1-(75/100)^5}{1-(65/100)^5}\right)^{2.5} = 0.691$$

The exponent of weather function w is calculated as follows with the recommended value of the exponent $b_w = 0.446$:

$$w = \frac{(p_{SR} \cdot ToW)^{(b_w)}}{2} = \frac{(1.00 \cdot 0.151)^{0.446}}{2} = 0.215$$

Parameters p_{SR} and ToW take into account the rain events. A probability of driving rain p_{SR} is a constant parameter of the average distribution of the wind direction during rain events which be carried out by determining the wind direction during rain events, based on data from the nearest weather station. For interior structural elements $p_{SR} = 0$ and for horizontal elements subjected to rain events $p_{SR} = 1$.

The weather function $W(t)$ for a reference time t_0 is calculated as:

$$t_0 = \frac{28}{365} = 0.0767 \text{ years}$$

$$W(t) = \left(\frac{t_0}{t}\right)^w = \left(\frac{0.0767}{10}\right)^{0.215} = 0.351$$

The carbonation rate is calculated according to following formula with $R_{NAC,0}^{-1}$ being converted into (mm^2/year)/(kg/m^3):

$$A = \sqrt{2 \cdot 315.5 \cdot 10^{11} \cdot k_e \cdot k_c \cdot R_{NAC,0}^{-1} \cdot C_{CO2} \cdot 10^{-6}}$$
$$= \sqrt{2 \cdot 315.5 \cdot 10^{11} \cdot 0.691 \cdot 0.675 \cdot 13.25 \cdot 10^{-11} \cdot 789.83 \cdot 10^{-6}} = 1.76 \text{ mm/year}^{0.5}$$

Finally, including the model uncertainty factor ψ (recommended value $\Theta = 1$), the carbonation depth x_c in time t is calculated based on the formula:

$$x_c(t) = \theta \cdot A \cdot \sqrt{t} \cdot W(t) = 1.00 \cdot 1.76 \cdot \sqrt{10} \cdot 0.351 = 1.95 \text{ mm}$$

4. Literature

[1] fib – International Federation for Structural Concrete (2006) fib Bulletin 34: Model Code for Service Life Design. Lausanne, Switzerland.