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Example Manual

Concrete Carbonation – Papadakis Model

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Concrete carbonation according to Papadakis et al.

1. Introduction

This example demonstrates the estimation of carbonation depth x_c based on the Papadakis et al. model [1] for a bridge deck constructed with ordinary Portland cement (OPC) concrete of strength class C20/25. The model considers the mass conservation of CO_2, $Ca(OH)_2$, and C-S-H in concrete. For simplicity, the model is expressed in a reduced form that incorporates key mix parameters, environmental conditions, and exposure time.

The bridge deck is assumed to be exposed to outdoor conditions for 30 years, with a typical mix design (water-to-cement ratio $w/c = 0.55$), cement and aggregate densities, and an ambient relative humidity of RH = 70%. The CO_2 concentration in the atmosphere is taken as approximately 750 mg/m^3, and the uncertainty factor is set to 1.0.

2. Input variables

Notation	Variable	Value	Unit
ρ_c	Specific gravities of cement	3150	kg/m3
w	Unit content of water	165	kg/m3
c	Unit content of cement	300	kg/m3
RH	Ambient relative humidity	70	%
C_{CO2}	Content of CO_2 in the atmosphere	750	mg/m3
t	Time of exposure	30	years
a_1	Unit content of agreggate I	800	kg/m3
a_2	Unit content of agreggate II	400	kg/m3
a_3	Unit content of agreggate II	600	kg/m3
ρ_{a1}	Specific gravity of aggregate I	2650	kg/m3
ρ_{a2}	Specific gravity of aggregate II	2650	kg/m3
ρ_{a3}	Specific gravity of aggregate II	2650	kg/m3
Θ	Uncertainty factor of model	1.00	-

3. Deterministic Calculation and Comments

There can be two types of humidity functions considered in this calculation:

1) the original linear function; see the graph in the 'Carbonation depth lin. f_RH' sheet in the Excel template file, and
2) an alternative experimental function; see the graph in the 'Carbonation depth altern. f_RH' sheet in the Excel template file.

The aggregate content is calculated as:

$$a_{1,2,3} = a_1 + a_2 + a_3 = 800 + 400 + 600 = 1800 \text{ kg/m}^3$$

The specific gravity of aggregates is:

$$\rho_a = \frac{a_{1,2,3}}{\frac{a_1}{\rho_{a_1}} + \frac{a_2}{\rho_{a_2}} + \frac{a_3}{\rho_{a_3}}} = \frac{1800}{\frac{800}{2650} + \frac{400}{2650} + \frac{600}{2650}} = 2650 \text{ kg/m}^3$$

For RH = 70%, the values of $f(RH)$ are $f(RH) = 0.30$ for the linear function and $f(RH) = 0.46$ for the experimental function, respectively.

The carbonation rate without consideration of relative humidity, A_0, can be assessed as:

$$A = 0.35\rho_c \frac{\left(\frac{w}{c} - 0.3\right)}{\left(1 + \frac{\rho_c w}{1000c}\right)} \sqrt{\left(1 + \frac{\rho_c w}{1000c} + \frac{\rho_c a_{1,2,3}}{\rho_a c}\right) C_{CO2} \frac{24}{44} \cdot 10^{-6}}$$
$$= 0.35 \cdot 3150 \cdot \frac{\left(\frac{165}{300} - 0.3\right)}{\left(1 + \frac{3150 \cdot 165}{1000 \cdot 300}\right)} \sqrt{\left(1 + \frac{3150 \cdot 165}{1000 \cdot 300} + \frac{3150 \cdot 1800}{2650 \cdot 300}\right) \cdot 750 \cdot \frac{24}{44} \cdot 10^{-6}}$$
$$= 6.41\ \text{mm/year}^{0.5}$$

Finally, including the model uncertainty factor ψ, the carbonation depth x_c in time t is calculated as:

$$x_c(t) = \theta \cdot A_0 \cdot f(RH) \cdot \sqrt{t}$$

Using the linear relative humidity function it leads to:

$$x_c(t) = \theta \cdot A_0 \cdot f(RH) \cdot \sqrt{t} = 1.00 \cdot 6.41 \cdot 0.300 \cdot \sqrt{30} = 10.53\ \text{mm}$$

For the alternative experimental relative humidity function the carbonation depth is:

$$x_c(t) = \theta \cdot A_0 \cdot f(RH) \cdot \sqrt{t} = 1.00 \cdot 6.41 \cdot 0.463 \cdot \sqrt{30} = 16.25\ \text{mm}$$

Note: Sometimes the CO_2 concentration can be set in parts per million by volume (ppm). For easier conversion see the ‘C_CO2’ sheet in the Excel template file, where the temperature of ambient air 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.

4. Literature

[1] Papadakis, V.G., Fardis, M.N. & Vayenas, C.G. (1992) Effect of composition, environmental factors and cement-lime mortar coating on concrete carbonation. Materials and Structures, 25, 293–304.