Accelerated Corrosion of Steel Reinforcement in Concrete: Experimental tests & 3D FE Analysis

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Outline

- Introduction & motivation
- Coupled 3D chemo-hygro-thermo-mechanical model for concrete
- Modeling of processes after depassivation of steel
- Experimental tests - accelerated corrosion
  - Corrosion induced damage
  - „Transport" of corrosion products
- Numerical analysis
  - Callibration of the model
  - Accelerated vs. natural corrosion
- Summary and conclusions

Introduction & motivation

- Corrosion of reinforcement significantly influence durability of reinforced concrete (RC) structures
- Reason for corrosion: electro-chemical reaction of steel due to carbonation of concrete or due to influence of chlorides

- Consequences:
  - reduction of steel cross-section area
  - damage of concrete cover
  - decrease of ductility of steel (pitting effect)
  - degradation of bond resistance (spalling)
- Reliable 3D numerical model useful for:
  - prediction of durability of RC structures (new & existing)
  - formulation of simple engineering models & design rules
  - effect of accelerated corrosion

Processes to be modeled

- Non-mechanical processes to compute corrosion rate:

  Before depassivation of reinforcement:

  - Transport of capillary water (hysteretic behavior: wetting-drying)
  - Transport of heat
  - Transport of oxygen and chloride through the concrete cover
  - Immobilization of chloride in concrete
  - Transport of OH^- ions through electrolyte in concrete pores
  - Cathodic and anodic polarization

  After depassivation (active corrosion phase):

  - Transport of capillary water (hysteretic behavior)
  - Transport of oxygen
  - Transport of rust
  - Creep of concrete

- Mechanical processes:
  - Damage and cracking of concrete
- Interaction between mechanical and non-mechanical processes in both directions

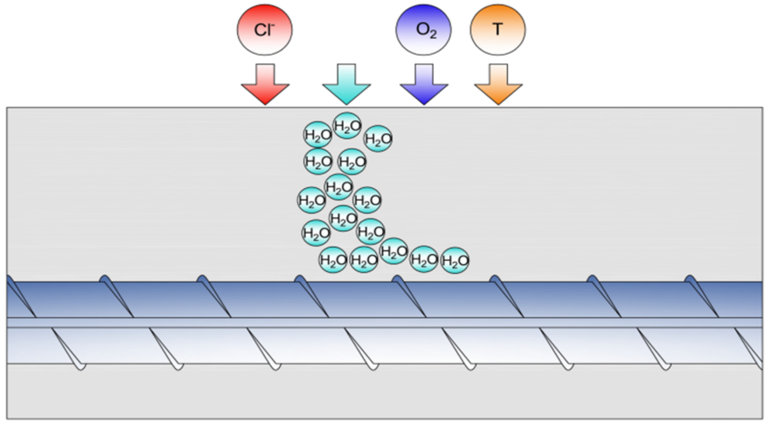
Theoretical framework

- Continuum mechanics
  - Green-Lagrange strain tensor
  - Co-rotational stress tensor
- Irreversible thermodynamics
- Mechanical model - microplane model for concrete based on the relaxed kinematic approach
- Discretization method - standard finite elements
- Smeared crack concept with crack band method as a localization limiter

Modelling processes after depassivation: active corrosion phase

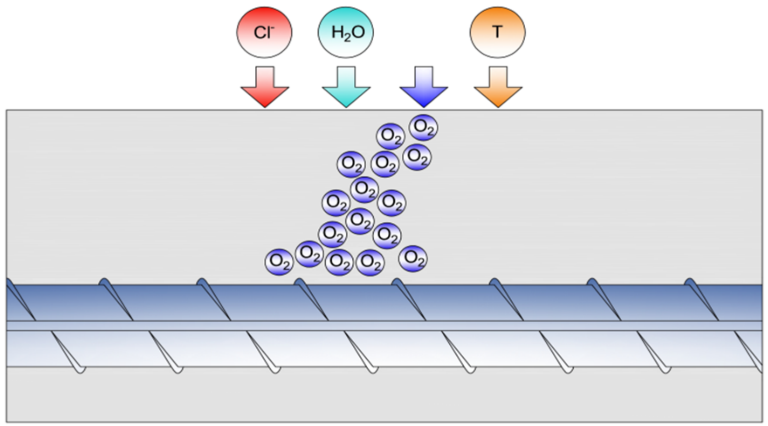
- Hysteretic moisture behavior of concrete

$$\rho_w \frac{\partial \theta_w(h)}{\partial h}\frac{\partial h}{\partial t} = \nabla \cdot (\delta_v(h) p_{v,sat} \nabla h)$$



- Transport of oxygen

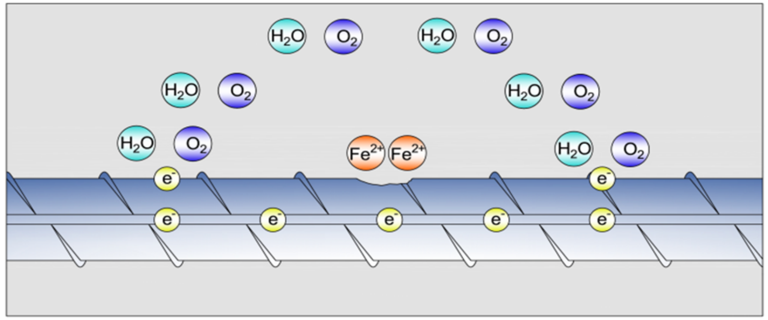
$$\theta_w \frac{\partial C_o}{\partial t} = D_w(\theta_w)\nabla\theta_w \nabla C_o + \nabla \cdot [\theta_w D_o(\theta_w)\nabla C_o]$$



Modelling processes after depassivation: active corrosion phase

- Oxygen consumption

$$D_o(S_w, p_c)\frac{\partial C_o}{\partial n}\bigg|_{cathode} = -k_c i_c \quad D_o(S_w, p_c)\frac{\partial C_o}{\partial n}\bigg|_{anode} = -k_a i_a$$

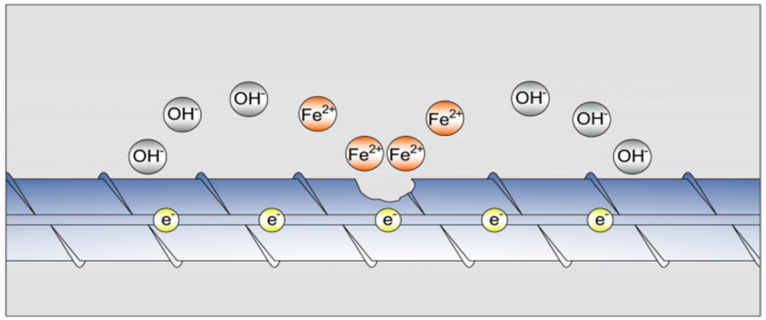


- Butler-Volmer kinetics

$$i_c = i_{0c}\frac{C_o}{C_{ob}}e^{2.3(\Phi_{0c}-\Phi)/\beta_c} \qquad i_a = i_{0a}e^{2.3(\Phi-\Phi_{0a})/\beta_a}$$

- Electric current through electrolyte

$$\boldsymbol{i} = -\sigma(S_w, p_c)\nabla\Phi$$



- Electrical charge conservation

$$\nabla^2\Phi = 0$$

Modelling processes after depassivation: active corrosion phase

- Rate of rust production

$$J_r = i_r i_a \qquad m_r = J_r \Delta t A_r$$

- Rust transport through pores and cracks

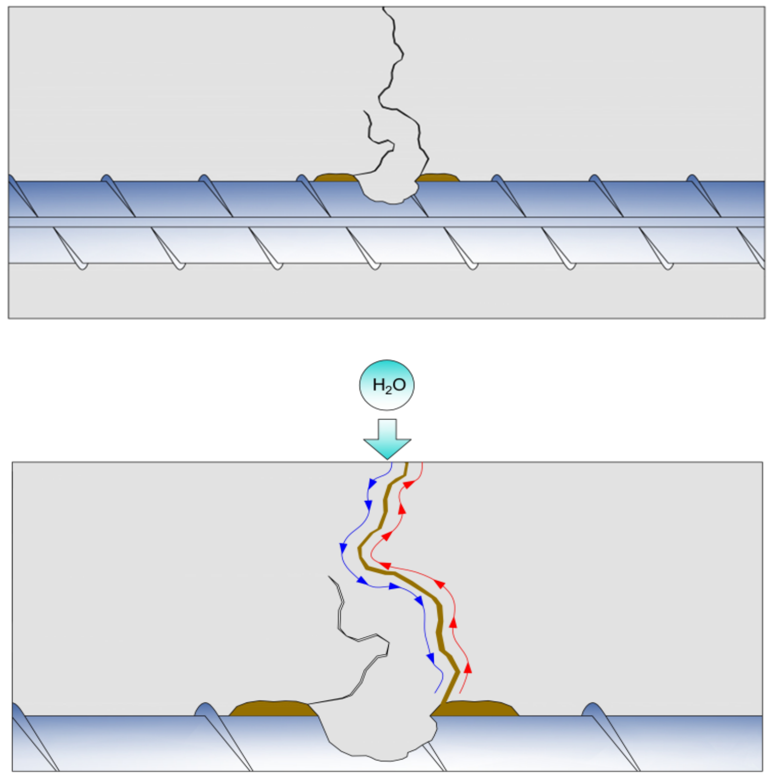
$$\theta_w \frac{\partial R}{\partial t} = \nabla \cdot \left[\theta_w D_r(\theta_w)\nabla R\right] + D_w(\theta_w)\nabla \theta_w \nabla R$$

- Inelastic radial expansion due to corrosion

$$\Delta l_r = \frac{m_r}{A_r}\left(\frac{1}{\rho_r} - \frac{r}{\rho_s}\right)$$

- Mechanical response

$$\nabla\left[D_m(u,\theta_w,T)\nabla u\right] + \rho b = 0$$



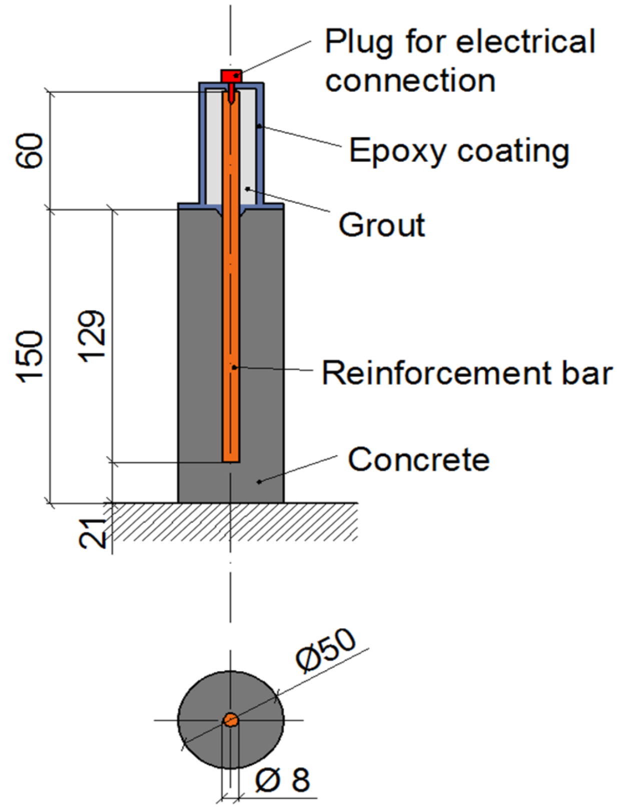
Accelerated corrosion tests on concrete cylinders

Performed tests on approximately 400 concrete cylinders

- Cylinder diameter 50 - 100 mm
- Reinforcement ϕ 8 to 16 mm
- Different loading scenaria
- Concrete: f_c= 40 MPa, w/c= 0.70

Aims:

- Calibration of the numerical model
- Study the effect of accelerated corrosion on corrosion induced damage



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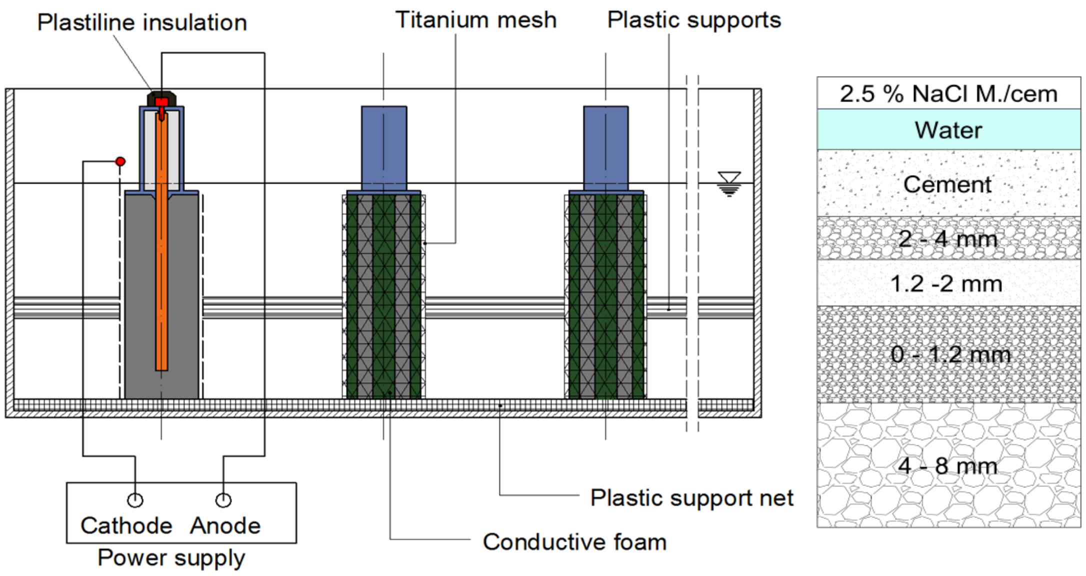
Accelerated corrosion tests: Test-setup

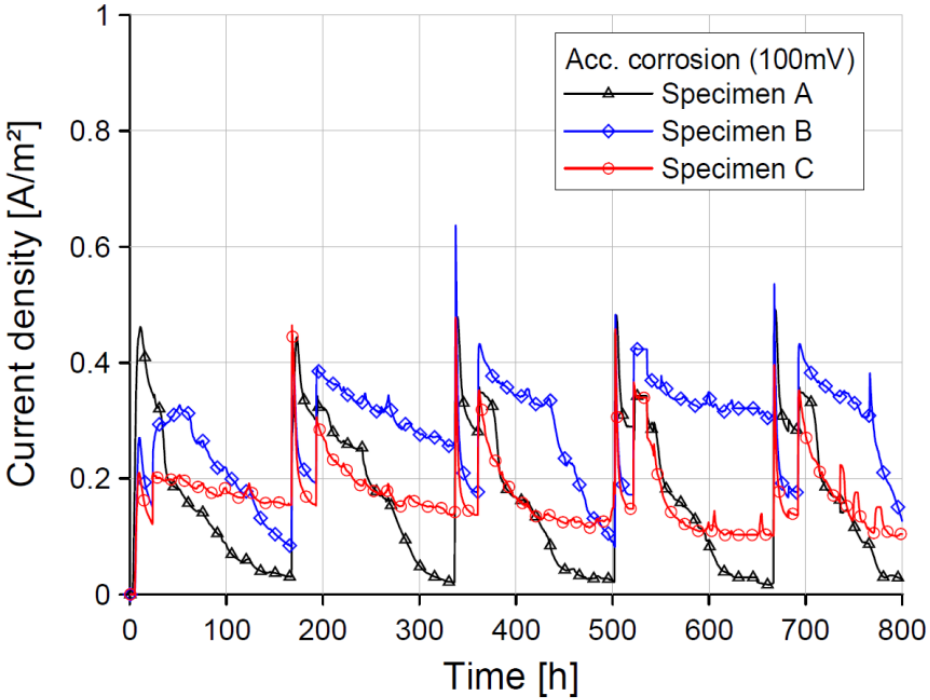


Accelerated corrosion test				
Imposed potential 100 mV	Imposed potential 500 mV	Geometry		
Specimen	Specimen	Specimen diameter	Reinf. Bar diameter	Ratio
(-)	(-)	(mm)	(mm)	(cover/diameter)
A (50/Φ8)	D (50/Φ8)	50	8	2.63
B (50/Φ8)	E (50/Φ8)			
C (50/Φ8)	F (50/Φ8)			

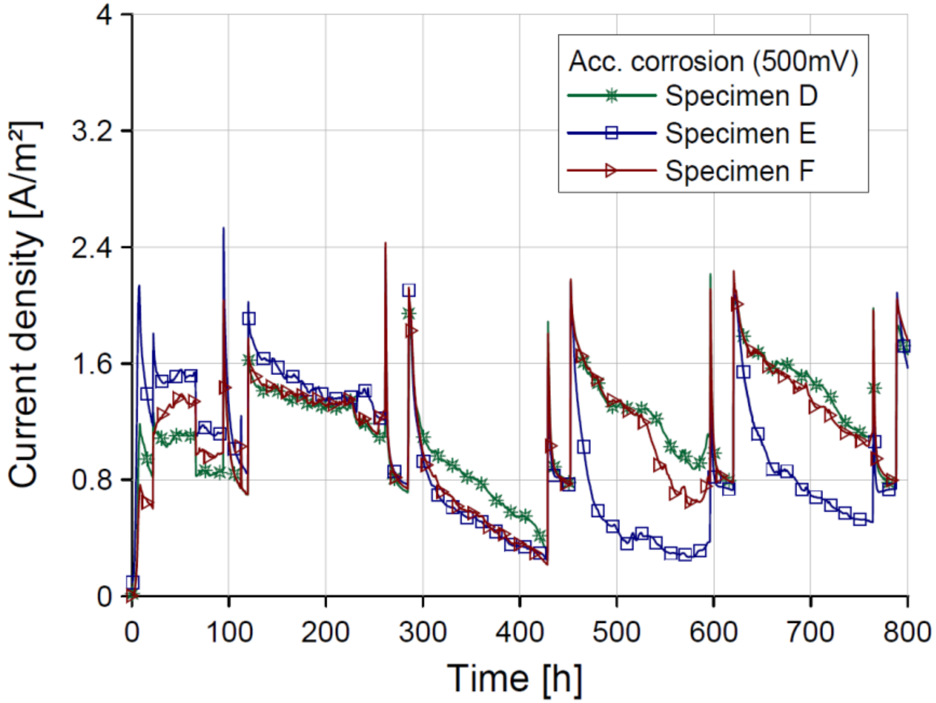
Accelerated corrosion test results

(splash conditions, cylinder 50/Φ8)

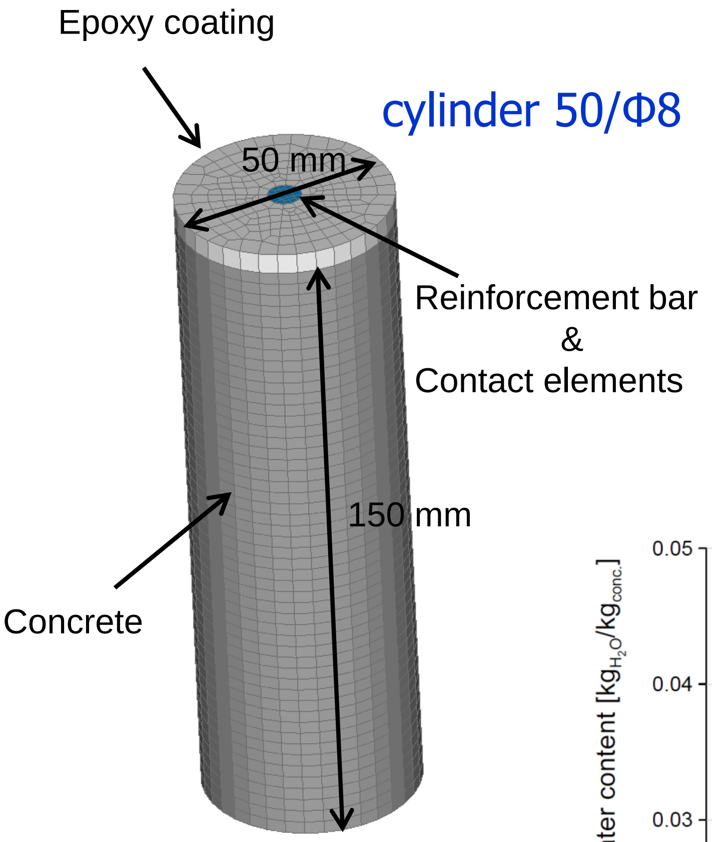
Imposed potential 100 mV, first crack after 20 days

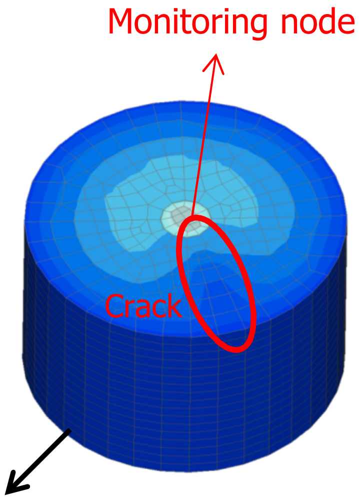


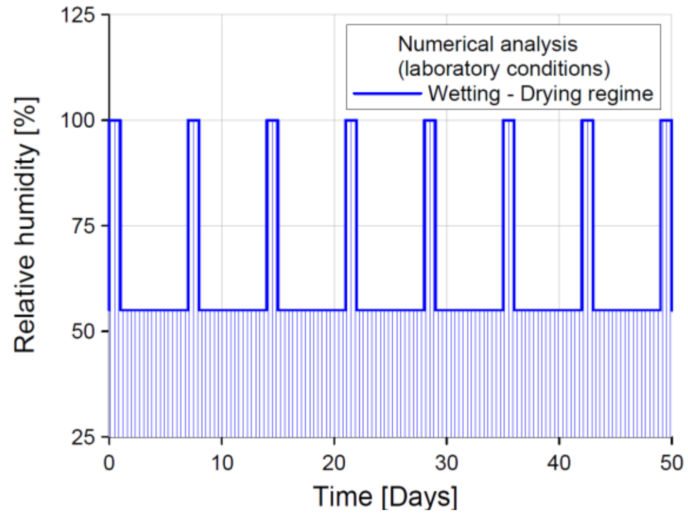
Imposed potential 500 mV, first crack after 6 days

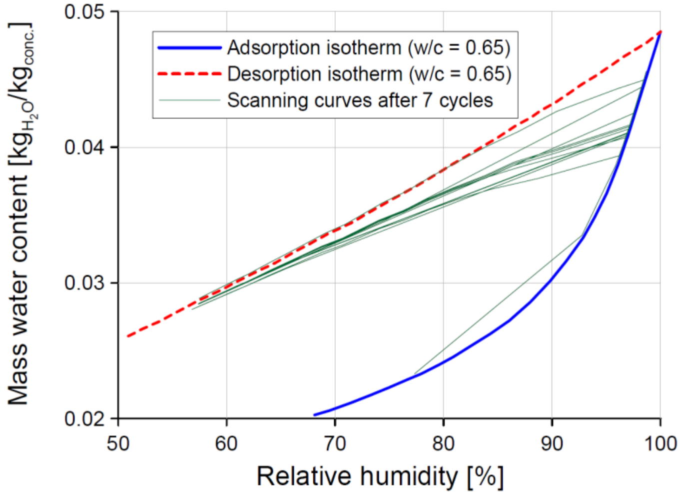


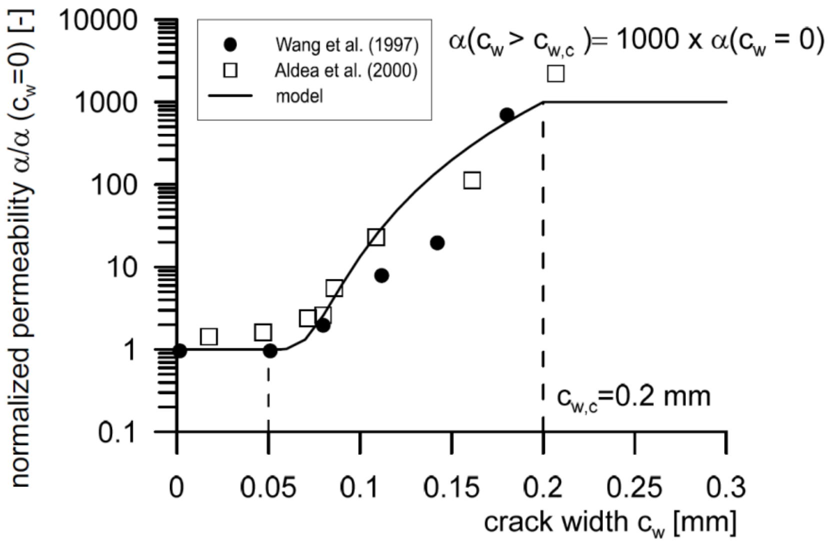
Accelerated corrosion – numerical simulation











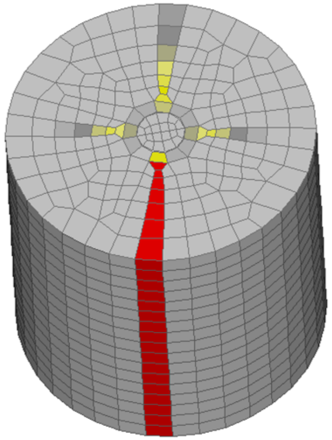
Mechanical properties:

E_c= 31.60 GPa
f_t= 3.10 MPa
f_c= 40.0 MPa
G_F= 55 J/m^2

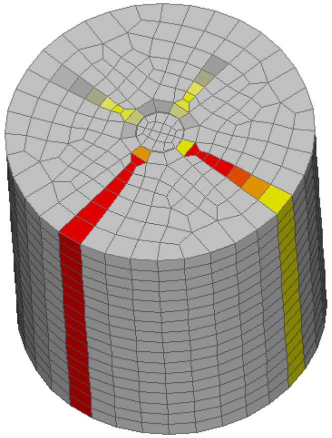
Hysteretic moisture model for concrete	
Sorption isotherms for	w/c=0.65
Water vapour permeability [s]	5.0×10^{-10}
Surface transfer humidity coeff. [m/s]	4.5×10^{-6}

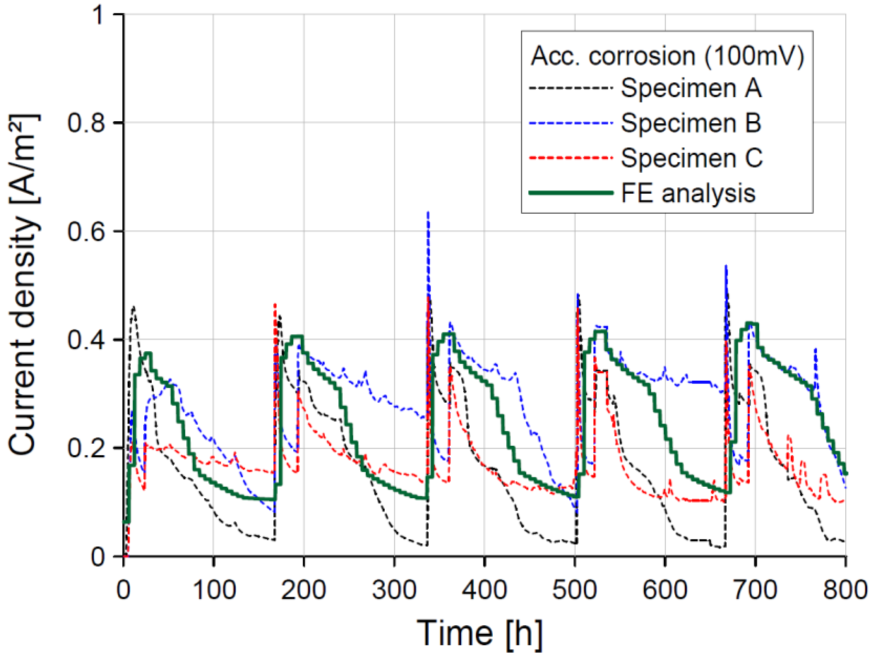
Analysis vs. Experiment (after calibration)

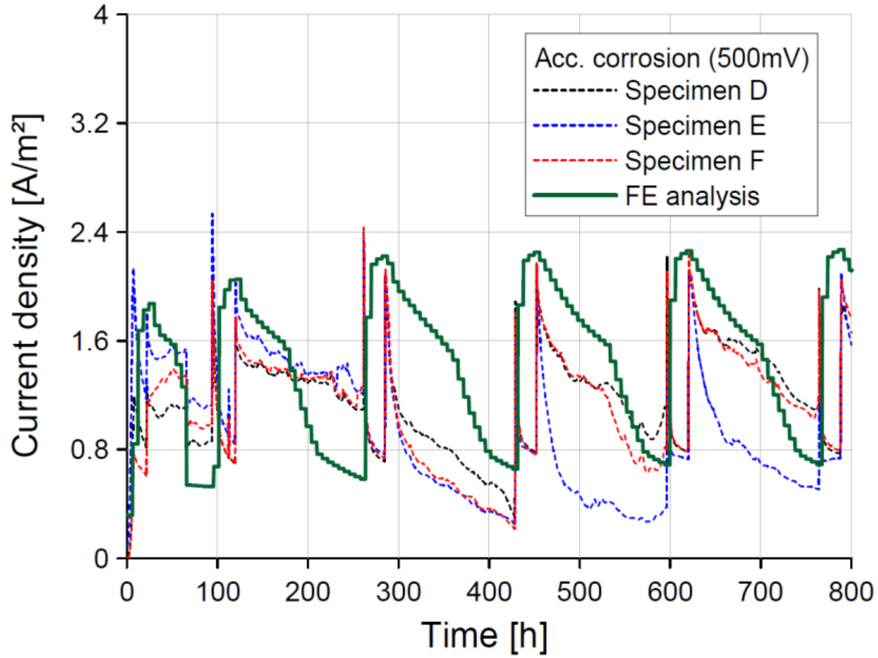
first crack after: 17 days vs. 20 days



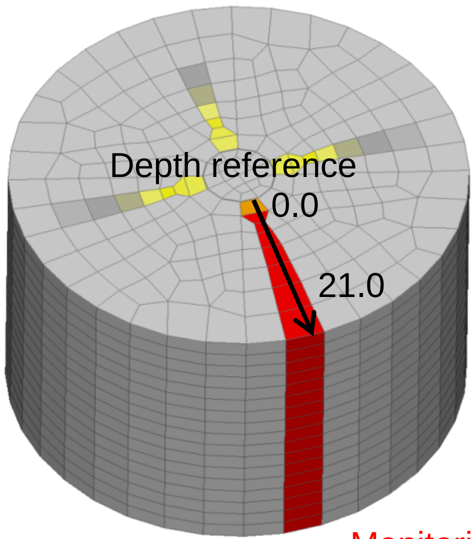
first crack after: 4 days vs. 6 days

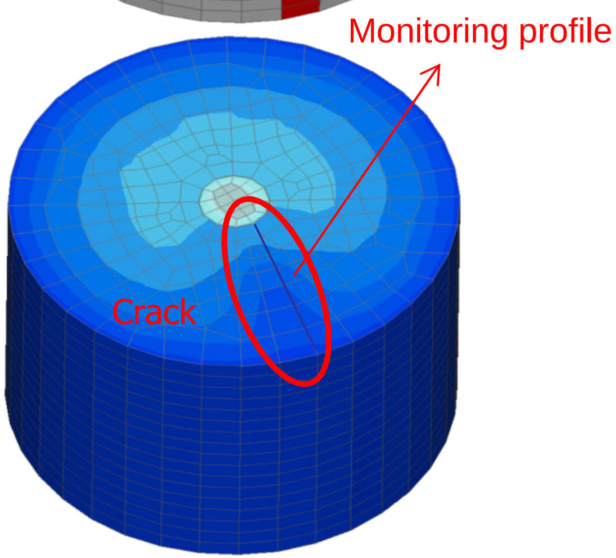




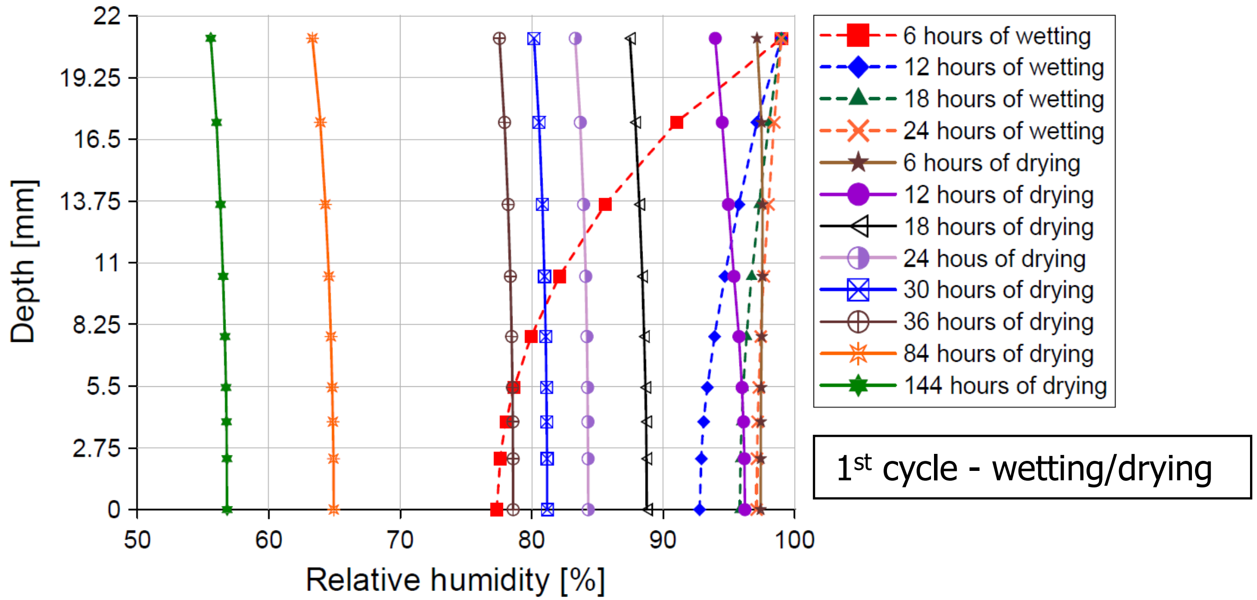


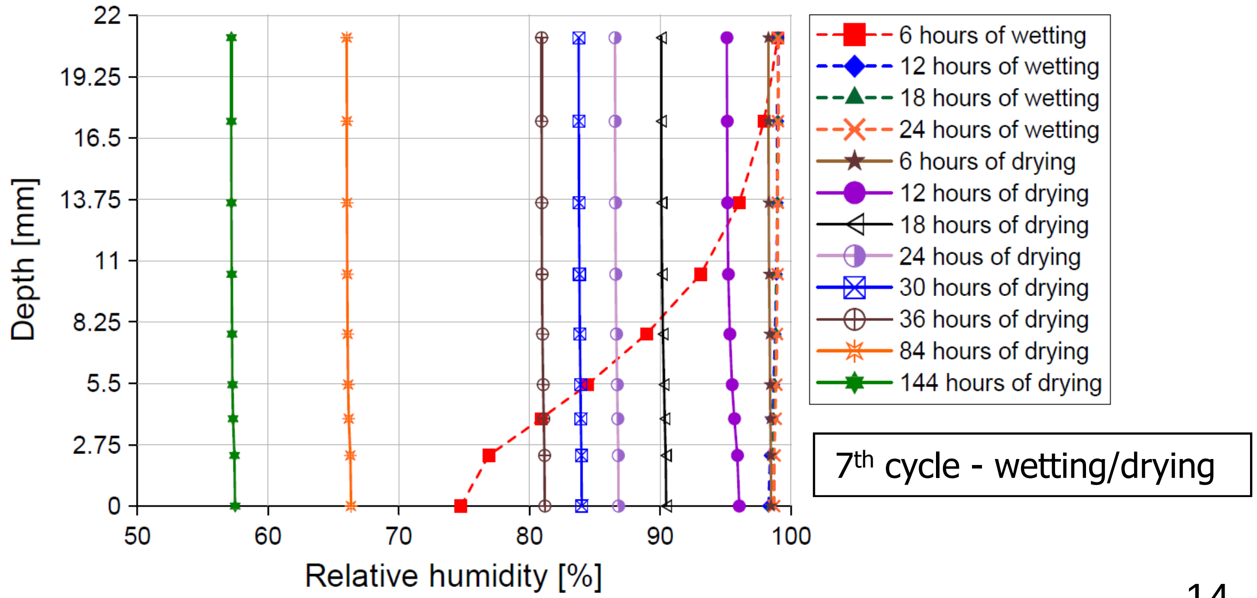
Distribution of humidity





Humidity distribution





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Conductivity of concrete

Conductivity of concrete depends on :

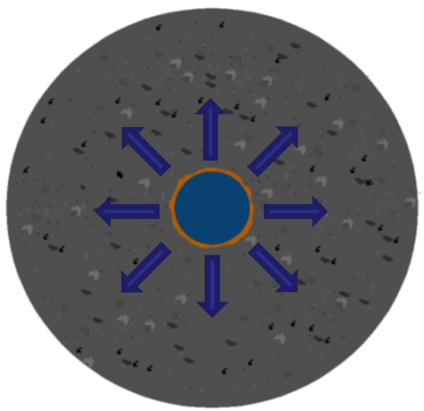
- Type of cement & additives
- Water/cement ratio
- Relative humidity, water content
- Chemical composition of pore water

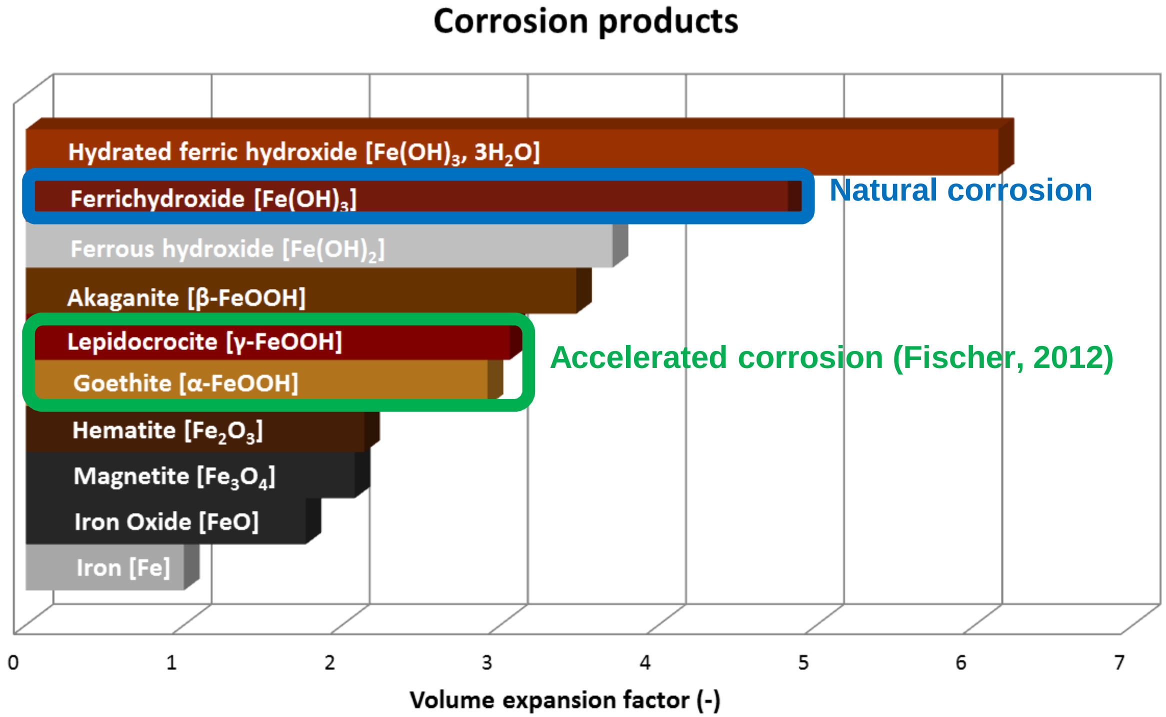
Measured only for saturation of 90% !

Result of the parametric study		
Electrical conductivity of concrete (w/c=0.7) $[10^{-3}\Omega^{-1}m^{-1}]$		
Saturation[%]	$\sigma_{natural,\ splash}$	$\sigma_{accelerated}$
50	2.75	8.75
55	3.00	9.54
60	4.28	13.61
65	8.70	27.67
70	9.52	30.27
75	10.50	33.39
80	11.50	36.57
85	12.50	39.75
90	13.50	42.93

$$\boldsymbol{i} = -\sigma(S_w, p_c)\nabla\Phi$$

Expansion of corrosion products





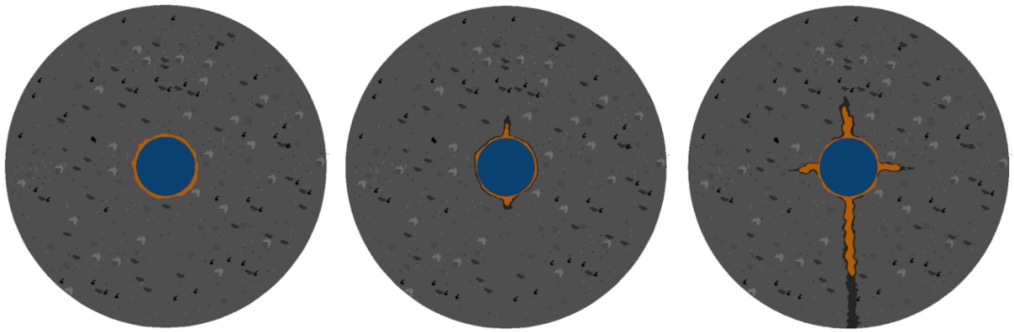
$$\alpha_r = \frac{\rho_s}{\rho_r} = 4.0$$

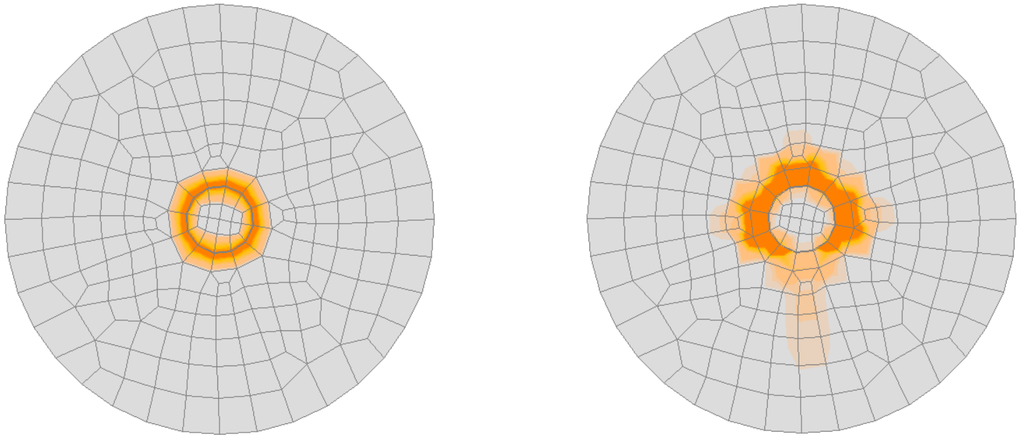
$$\alpha_r = \frac{\rho_s}{\rho_r} = 1.9$$

Expansion of corrosion products		
Natural corrosion [Ferric hydroxide $Fe(OH)_3$]	$J_r = 5.536\times10^{-7} i_a$	$\Delta l_r = \frac{m_r}{A_r}\left(\frac{1}{\rho_r} - \frac{0.523}{\rho_s}\right)$
Accelerated corrosion [Lepidocrocite, Goethit α-FeOOH, γ-FeOOH]	$J_r = 4.607\times10^{-7} i_a$	$\Delta l_r = \frac{m_r}{A_r}\left(\frac{1}{\rho_r} - \frac{0.623}{\rho_s}\right)$

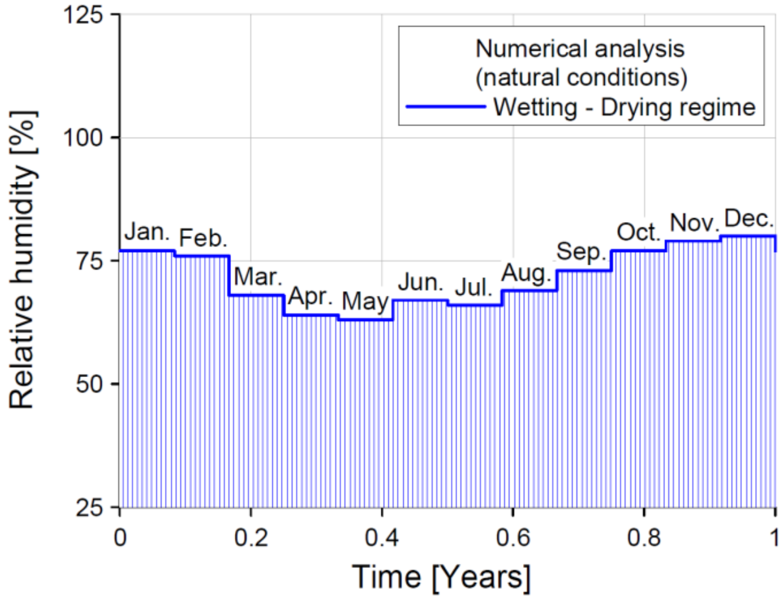
„Transport“ of rust

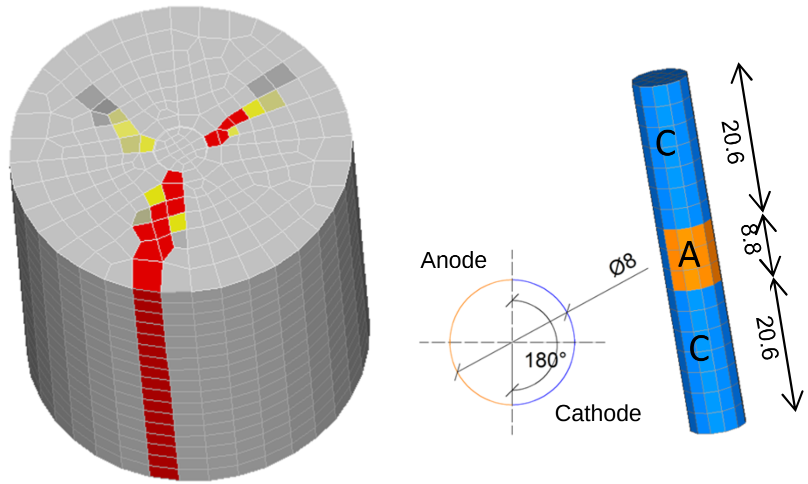
Initial rust diffusion coefficient			
	Natural	100 mV	500 mV
Rust diffusion coefficient D_R (m²/s)	2.2×10^{-16}	$3.2. \times 10^{-15}$	9.5×10^{-15}

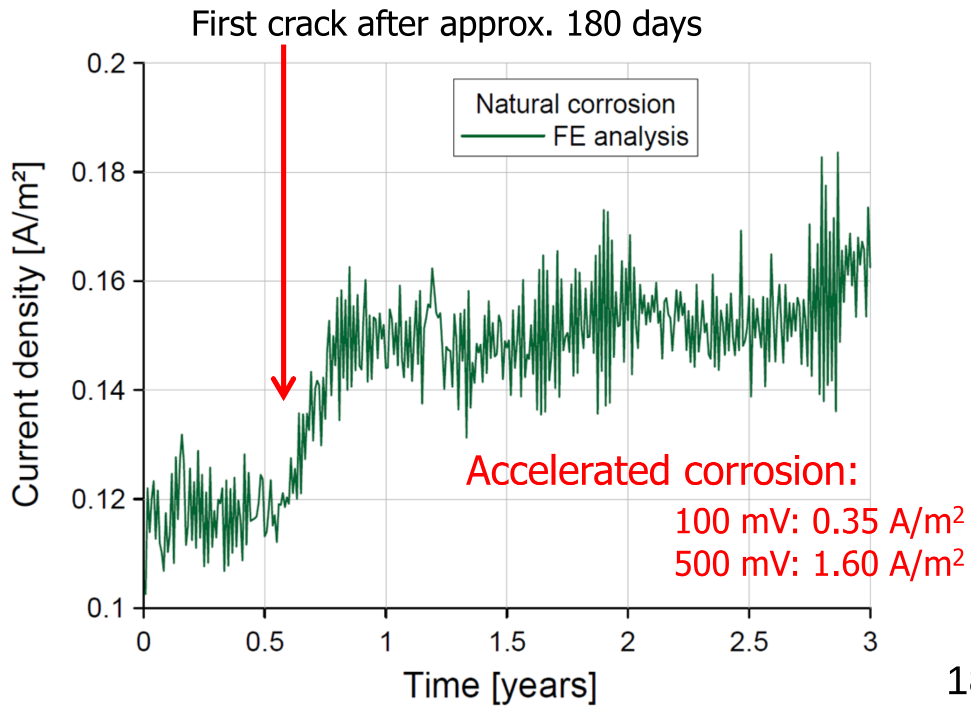




Natural corrosion (splash conditions)







Model parameters	
Faraday's constant, F (C/mol)	96486.7
Anodic exchange current density, i_{0a} (A/m^2)	1.875×10^{-4}
Cathodic exchange current density, i_{0c} (A/m^2)	6.25×10^{-6}
Anodic equilibrium potential, Φ_{0a} (V vs. SCE)	-0.780
Cathodic equilibrium potential, Φ_{0c} (V vs. SCE)	0.160
Tafel slope for anodic reaction, β_a (V)	0.06
Tafel slope for cathodic reaction, β_c (V)	0.160
Difusion coeff. for transport of rust (m^2/s)	2.2×10^{-16}

Summary and conclusions

- The coupled 3D CHTM model is able to replicate accelerated corrosion of reinforcement in concrete.
- Computed current density and related time of cracking and crack patterns are similar to the experimentally observed ones.
- The transport of rust through cracks in concrete plays important role in corrosion induced damage of concrete.
- In case of accelerated corrosion different types of products are produced with expansion factor lower of that observed in case of natural corrosion (red rust).
- For the present geometry and environmental conditions accelerated corrosion with imposed electric potential up to 500 mV yields to results that are comparable with the results obtained assuming natural conditions.