Evaluation of chloride-ingress models on concrete bridge exposed to deicing salts

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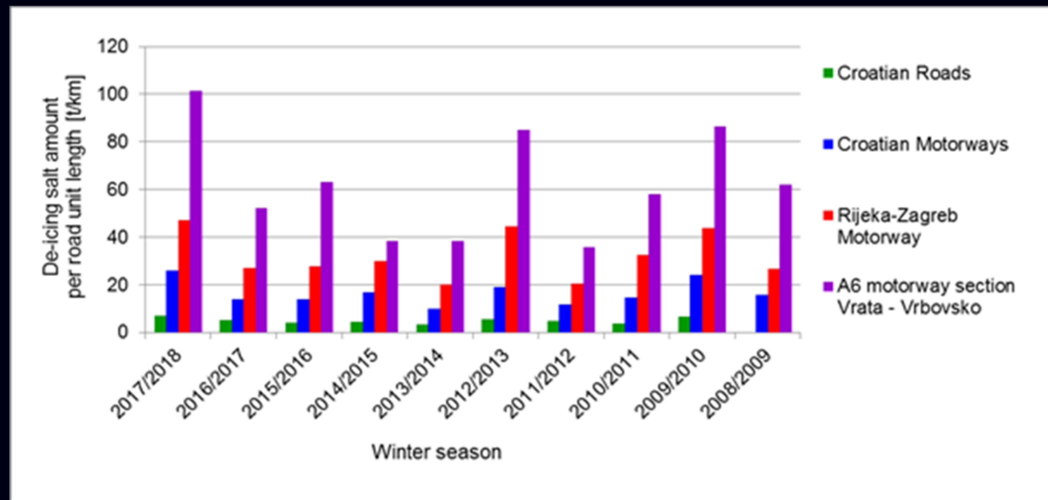
OUTLINE

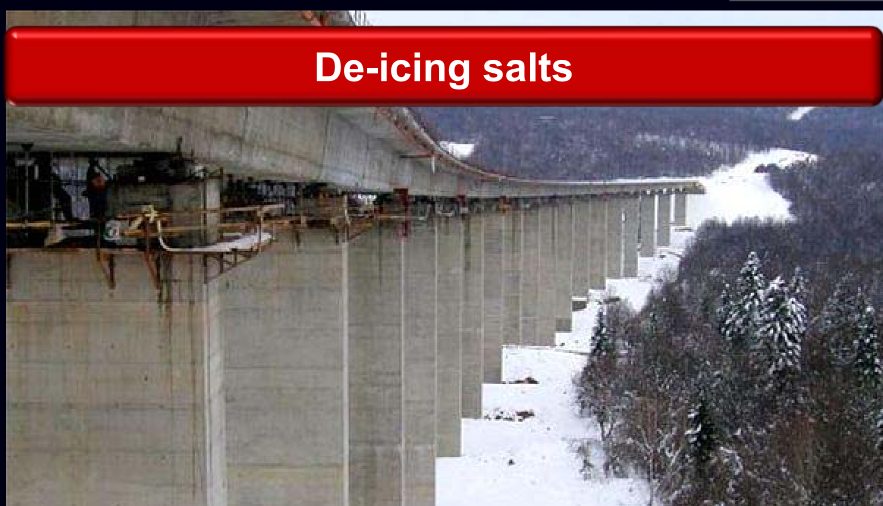
1. Introduction and motivation
2. 3D chemo-hygro-thermo mechanical model
3. Life-365
4. Application on case study
5. Conclusion

INTRODUCTION AND MOTIVATION

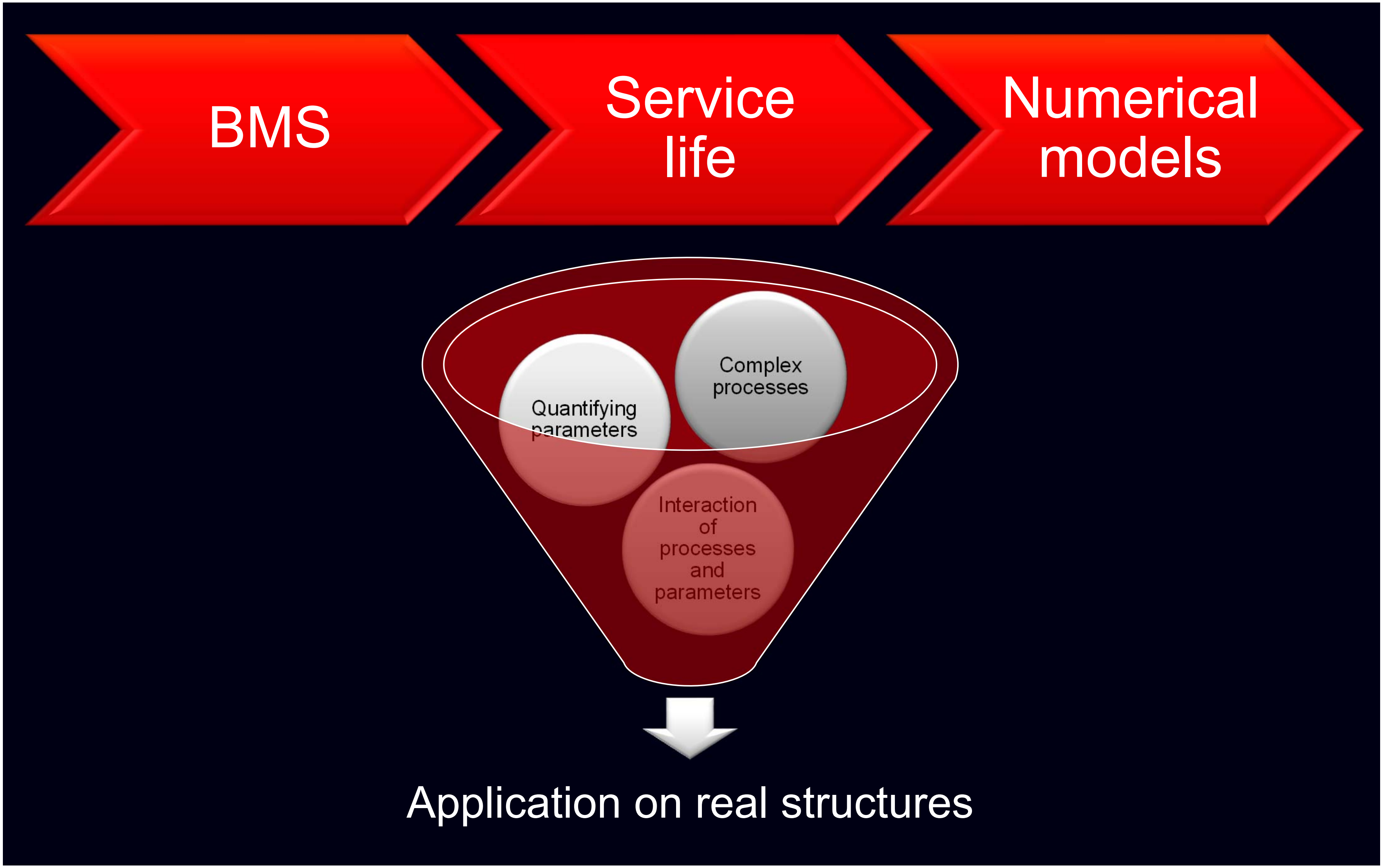
Corrosion of steel in concrete

- Major cause of deterioration of RC and PC bridges and service life reduction
- In the mountain area: average seasonal consumption of de-icing salts for each separate carriageway on motorway (two lanes) is 62 t/km



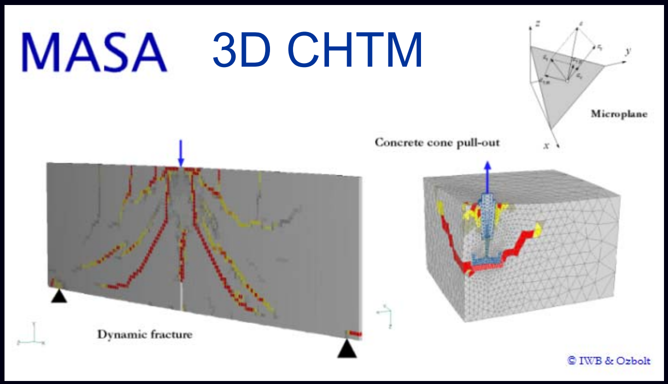


INTRODUCTION AND MOTIVATION



INTRODUCTION AND MOTIVATION

Application of chloride ingress models on case studies

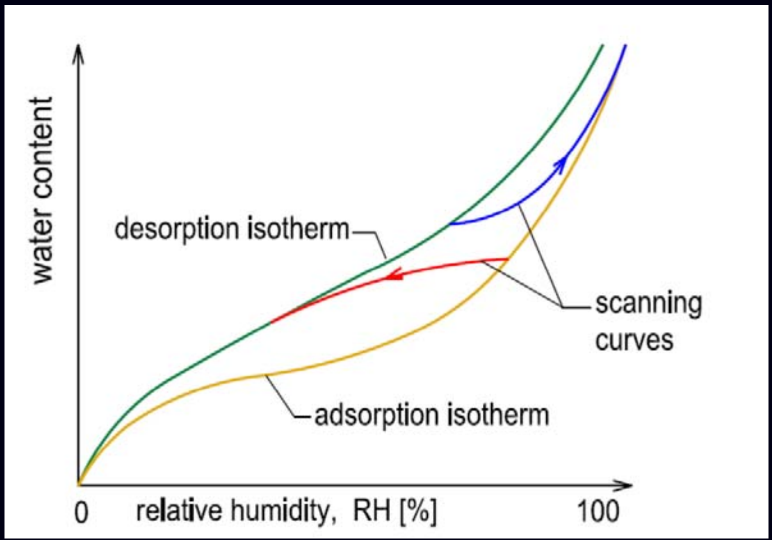


3D CHEMO- HYGRO-THERMO MECHANICAL MODEL

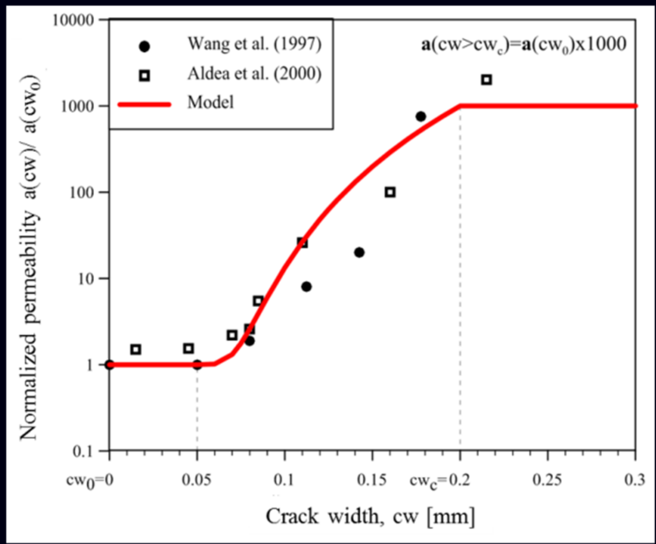
- Modelling physical, electrochemical and mechanical processes:
  - Transport of capillary water, heat, oxygen and chloride through the concrete cover
  - Immobilization of chloride in the concrete
  - Cathodic and anodic polarization
  - Transport of OH- ions through electrolyte in concrete pores
  - Mass sinks of oxygen on steel surface due to cathodic and anodic reaction
  - Distribution of electrical potential and current density
  - Transport of corrosion products in concrete and cracks
  - Concrete cracking due to mechanical and non-mechanical actions

3D CHEMO- HYGRO-THERMO MECHANICAL MODEL

- ❑ Realistic environmental and structural conditions
  - ❑ Surface water and chloride contents variable in time based on the meteorological data
  - ❑ Wetting–drying cycles
  - ❑ Impact of concrete crack and damage on water and chloride penetration in concrete



Adsorption, desorption and scanning curves for a concrete



Water diffusivity & permeability as a function of the crack width

Ožbolt et al. (2010, 2016)

3D CHTM model: Initial phase of corrosion

- Wetting – drying cycles
  - Changes in relative humidity
  - 2 isotherms: desorption and adsorption
- Distribution of chlorides
  - Diffusion + convection - binding by cement hydration product
- Distribution of temperature

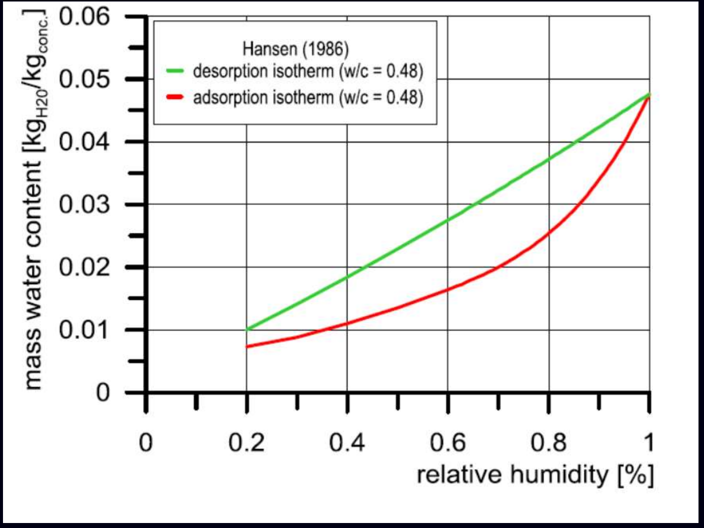
$$\rho_w \frac{\partial \theta_w(h)}{\partial t} = \rho_w \frac{\partial \theta_w(h)}{\partial h}\frac{\partial h}{\partial t} = \nabla \cdot \left(\delta_v(h) p_{v,sat} \nabla h\right)$$

$$\theta_w \frac{\partial C_c}{\partial t} = \left(\frac{\delta_v(h)}{\rho_w} p_{v,sat} \nabla h \cdot \nabla\right) C_c + \nabla \cdot \left(\theta_w D_c(\theta_w, T) \nabla C_c\right) - \frac{\partial C_{cb}}{\partial t}$$

$$\frac{\partial C_{cb}}{\partial t} = k_r \left(\alpha C_c - C_{cb}\right)$$

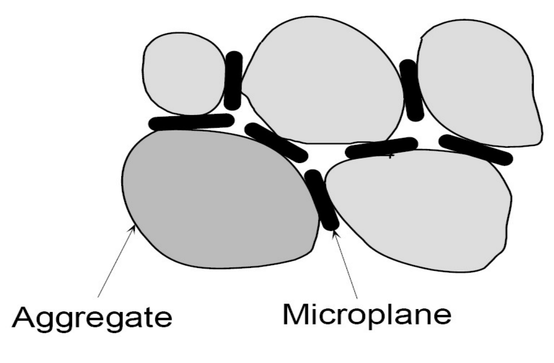
$$D_c(\theta_w, T) = D_{c,ref}\left[1 + \frac{(1-h(w))^4}{(1-h_c)^4}\right]^{-1} \cdot \exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

$$\lambda \Delta T + W(T) - c \cdot \rho \frac{\partial T}{\partial t} = 0$$



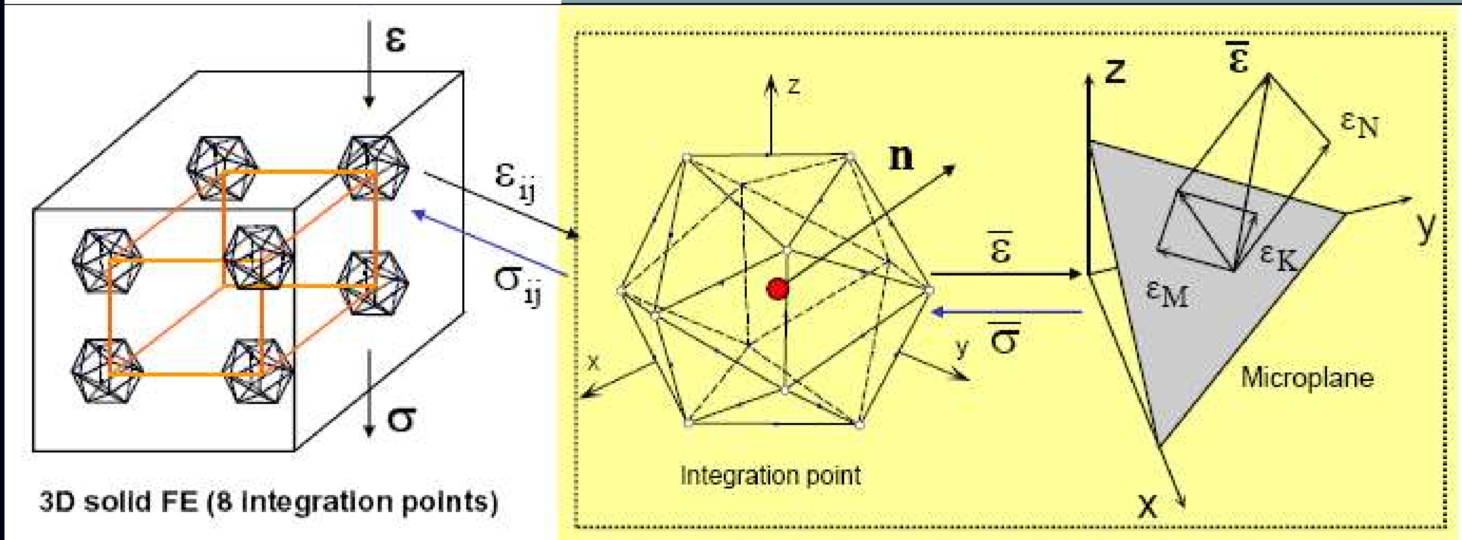
Ožbolt et al. (2016)

3D CHTM model: Microplane model for concrete



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

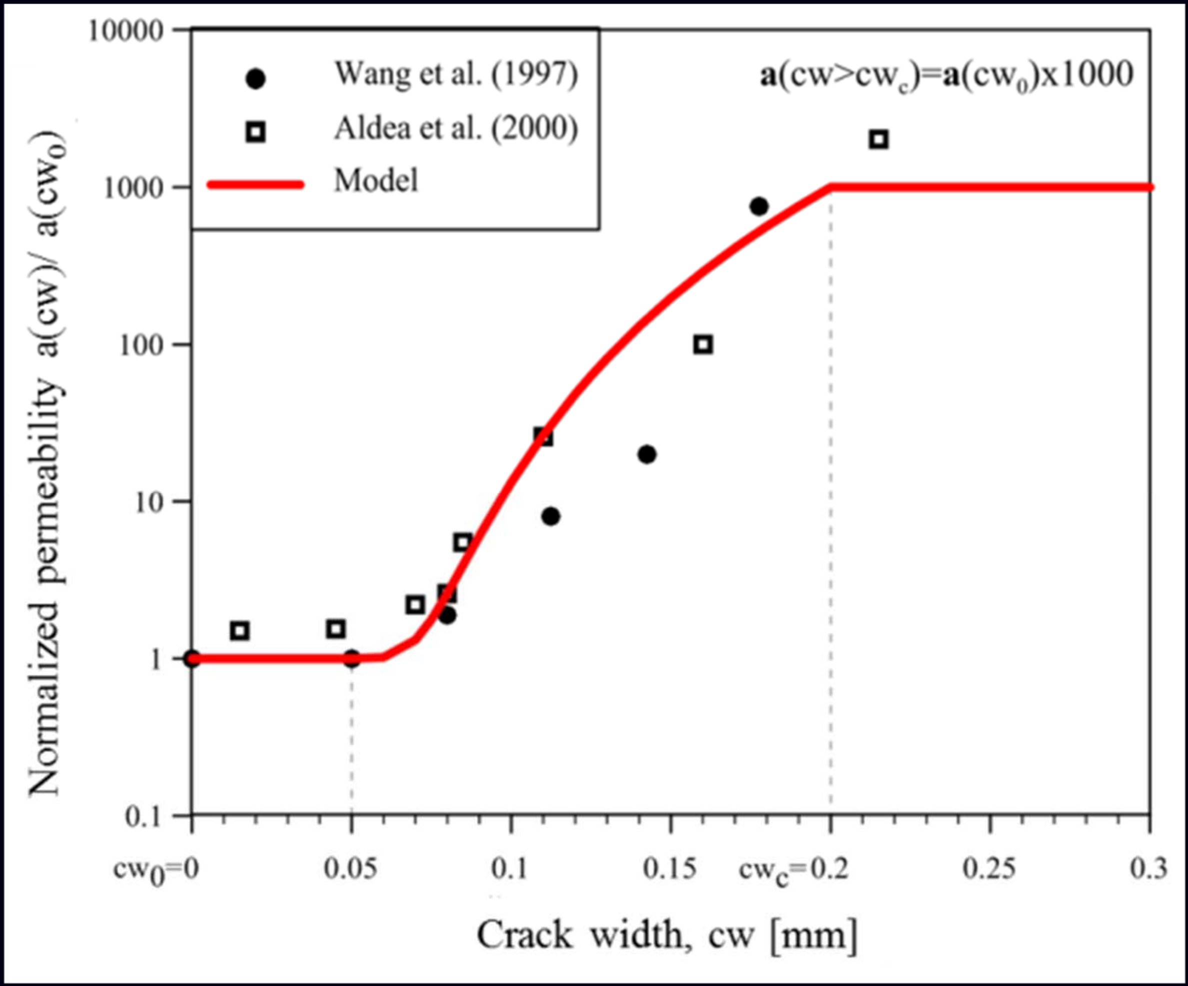
$$\varepsilon_{ij}=\varepsilon_{ij}^{m}+\varepsilon_{ij}^{T}+\varepsilon_{ij}^{w}+\varepsilon_{ij}^{corr}$$



Bažant & Oh (1983)
Ožbolt et al. (2001)
Ožbolt et al. (2005)

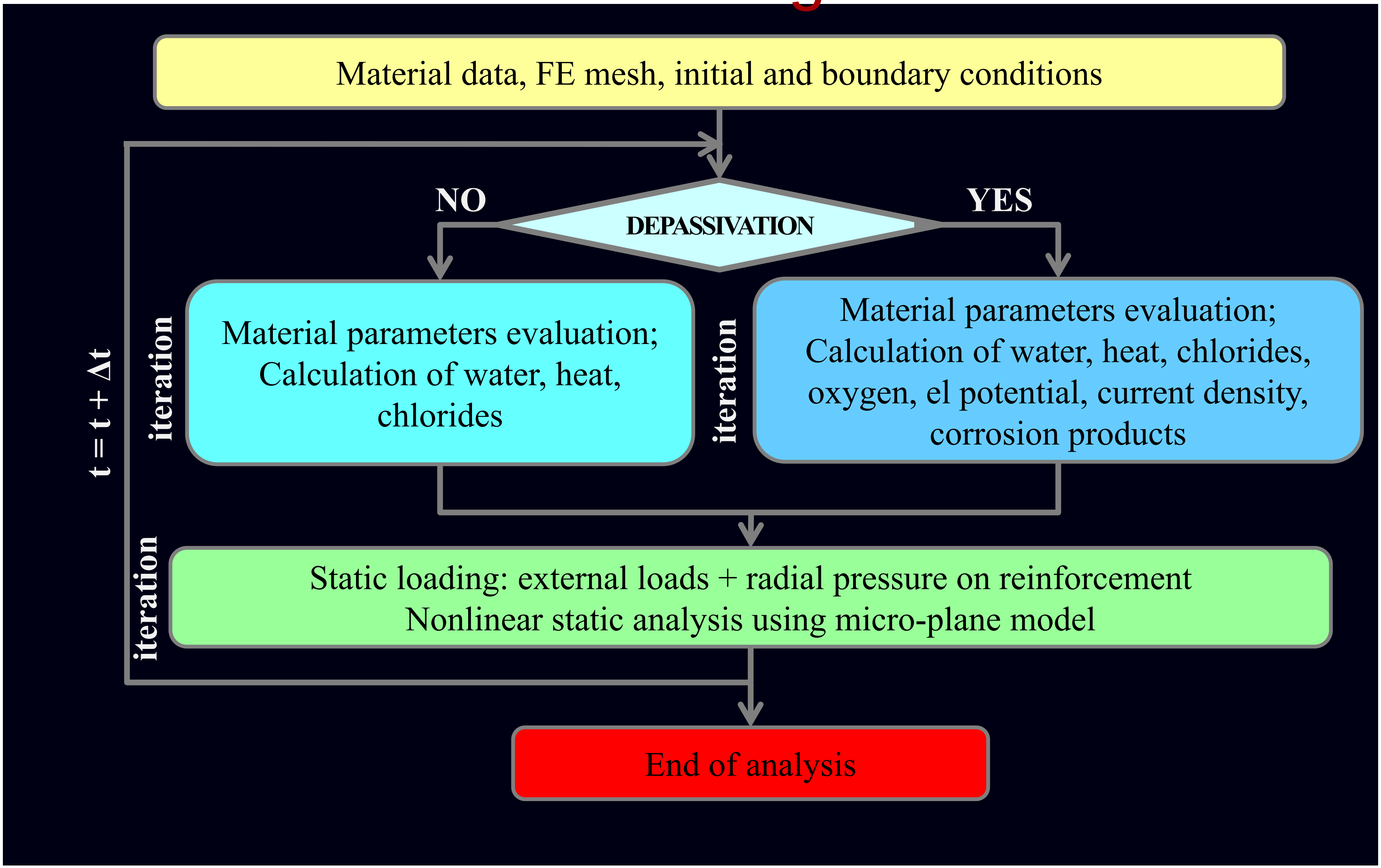
3D CHTM model: chemo-hygro-thermo-mechanical coupling

- Assumption: diffusivity (D) & permeability (K) - function of the crack width



Ožbolt et al. (2010.)

3D CHTM model: Numerical algorithm



Life-365

- ❑ Chloride ingress in un-cracked concrete
- ❑ Fick's second law
- ❑ Diffusion as dominant transport processes

$$\frac{dC}{dt} = D\frac{d^2C}{dx^2}$$

C - chloride content
D - apparent diffusion coefficient
x - depth from the exposed surface
t - time.

- ❑ Chloride diffusion coefficient is a function of time

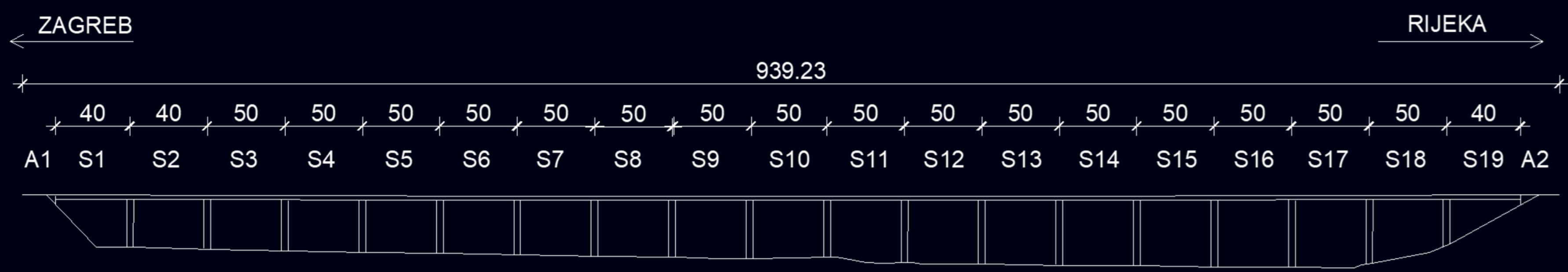
$$D_{ref} = D_{28} = 1 \cdot 10^{(-12.06+2.40w/c)}$$

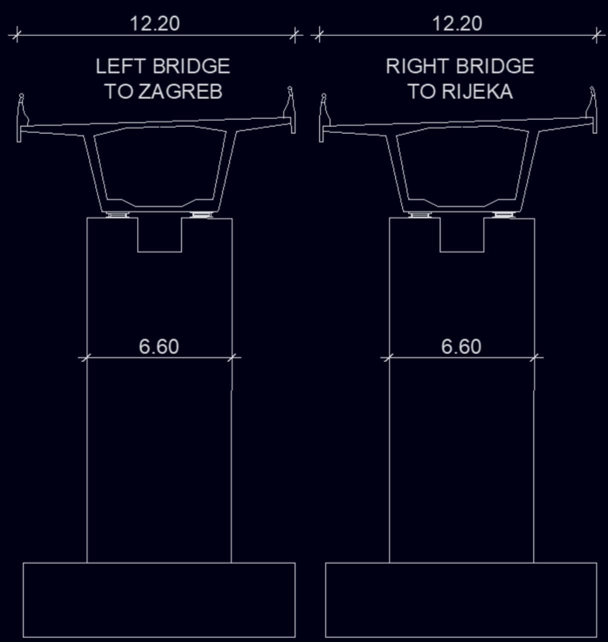
$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m$$

$$m = 0.2 + 0.4\left(\frac{\%FA}{50} - \frac{\%SG}{70}\right)$$

Thomas & Bentz (2018)

Case study: Zečeva Draga Viaduct





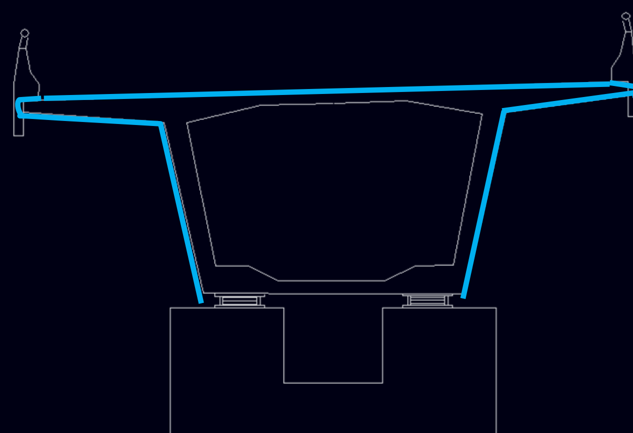
Two twin structures
Built in 2004 and 2007

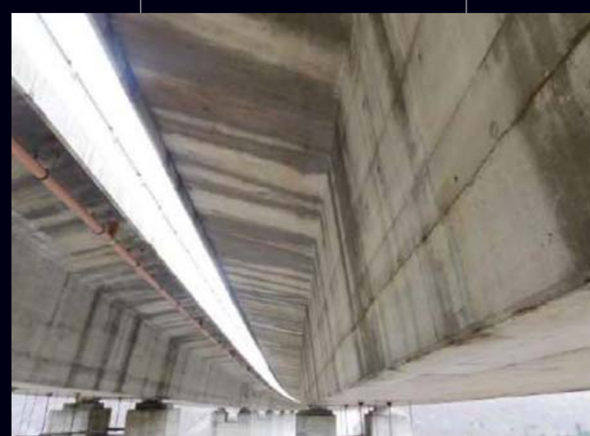
Kušter Marić et al. (2020)

Viadukt (2007)

Case study:
Zečeva Draga Viaduct

High consumption of de-iceying salts + Errors in design/ construction = Chloride-induced corrosion





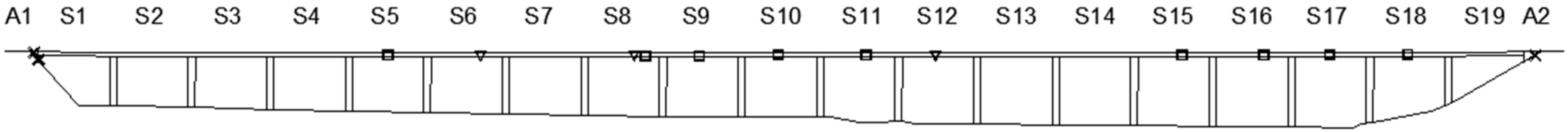
Material parameters used in 3D CHTM

Modulus of elasticity of concrete, E_c (MPa)	32500.0
Tensile strength, f_t (MPa)	3.13
Uniaxial compressive strength, f_c (MPa)	51.57
Fracture energy, G_F (J/m^2)	80.0
Thermal conductivity, λ (W/mK)	2.10
Heat capacity per unit mass of concrete, c (J/kgK)	900.0
Mass density of concrete, ρ_{con} (kg/m^3)	2480.0
Mass density of water, ρ_w (kg/m^3)	1000.0
Water volume in concrete at saturation, θ_{wd} (m^3/m^3)	0.10
Initial concrete porosity, p_c	0.10
Water/Cement ratio, w/c	0.48
Amount of cement gel in concrete, W_{gel} (kg/m^3)	448.00
Equivalent hydration time period, t_e (days)	180.00
Chloride binding rate coefficient, k_r (s^{-1})	5.00×10^{-7}
Chloride diffusion activation energy, U (kJ/mol)	44.60
Referent chloride diffusion coefficient in un-cracked concrete, $D_{c,ref,0}$ (m^2/s)	6.00×10^{-11}
Water vapor permeability, δ_v (s)	7.00×10^{-11}

Microclimate parameters used in 3D CHTM

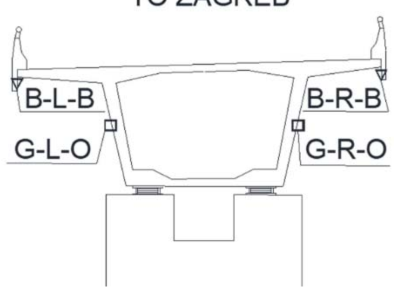
		WD1, WD2, WD3, Life365		WD1	WD2	WD3	noWD2		
		T (°C)	h (%)	C_c (kg/m^3)	C_c (kg/m^3)	C_c (kg/m^3)	T (°C)	h (%)	C_c (kg/m^3)
Month	I.	1,0	82	9,00	12,00	20,00	10,2	77	4,60
	II.	2,0	78	9,00	12,00	20,00	10,2	77	4,60
	III.	6,0	73	6,00	8,00	13,00	10,2	77	4,60
	IV.	10,0	70	1,00	1,00	4,00	10,2	77	4,60
	V.	14,0	71	1,00	1,00	4,00	10,2	77	4,60
	VI.	18,0	72	0,00	0,00	0,00	10,2	77	4,60
	VII.	20,0	72	0,00	0,00	0,00	10,2	77	4,60
	VIII.	19,0	76	0,00	0,00	0,00	10,2	77	4,60
	IX.	15,0	80	0,00	0,00	0,00	10,2	77	4,60
	X.	10,0	82	1,00	1,00	4,00	10,2	77	4,60
	XI.	5,0	84	6,00	8,00	13,00	10,2	77	4,60
	XII.	2,0	84	9,00	12,00	20,00	10,2	77	4,60

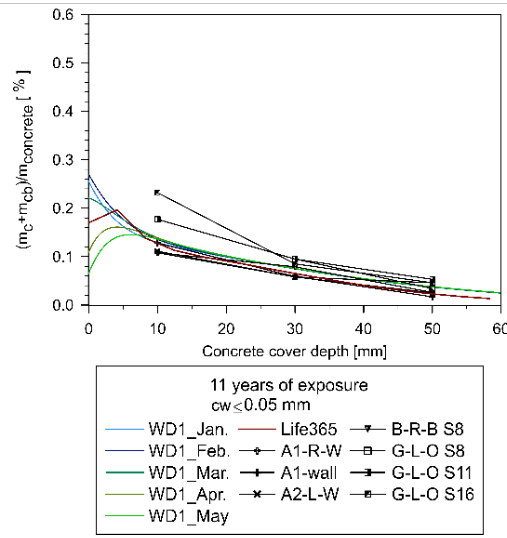
Comparison of numerical and measured chloride content

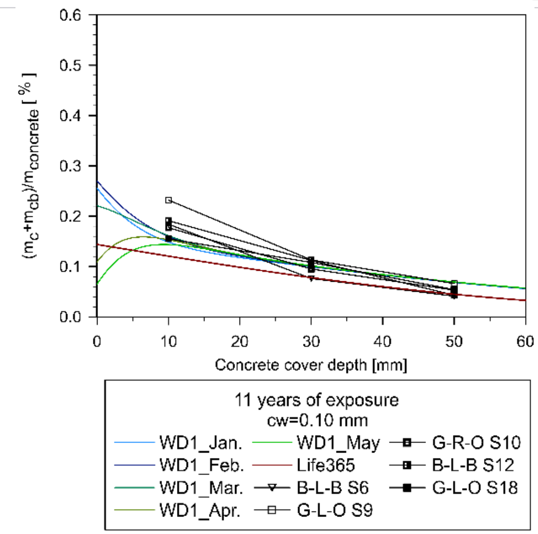


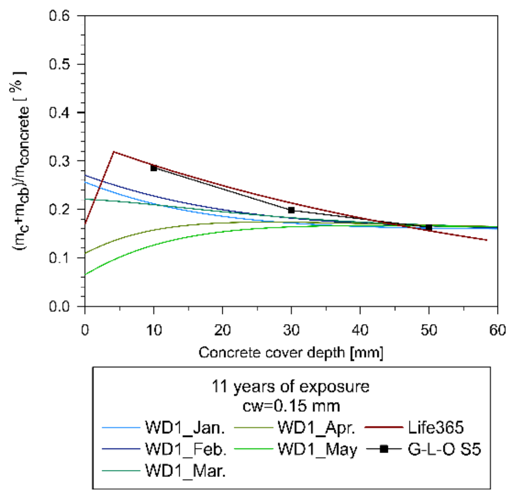
11 years of exposure

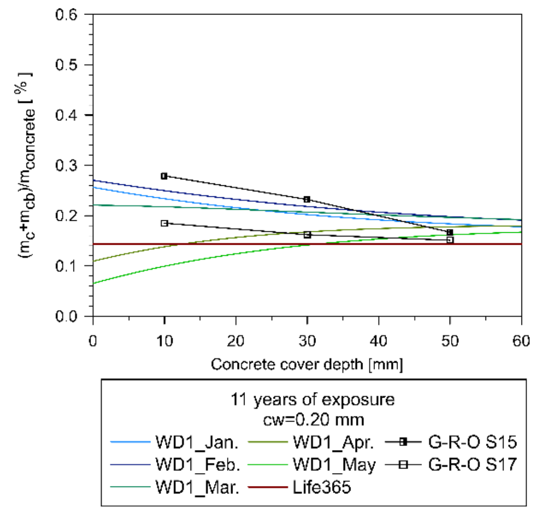
Exposure class: WD1





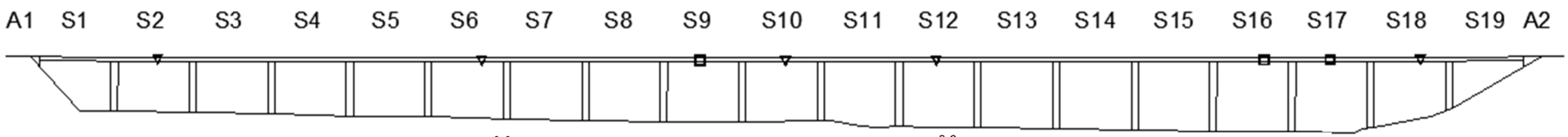






Kušter Marić et al. (2020)

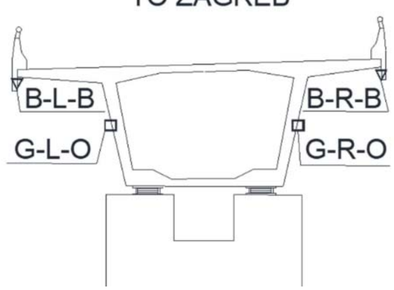
Comparison of numerical and measured chloride content

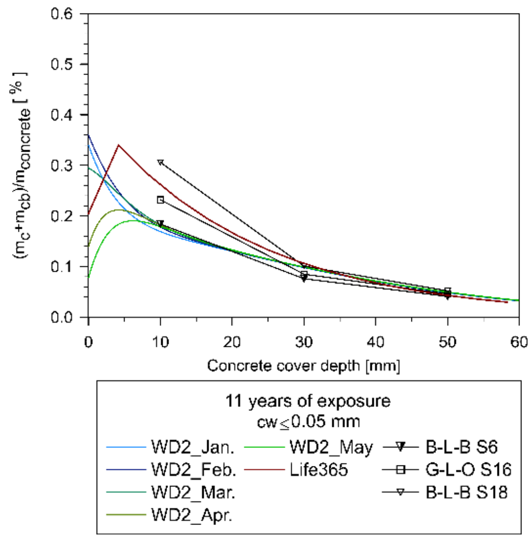


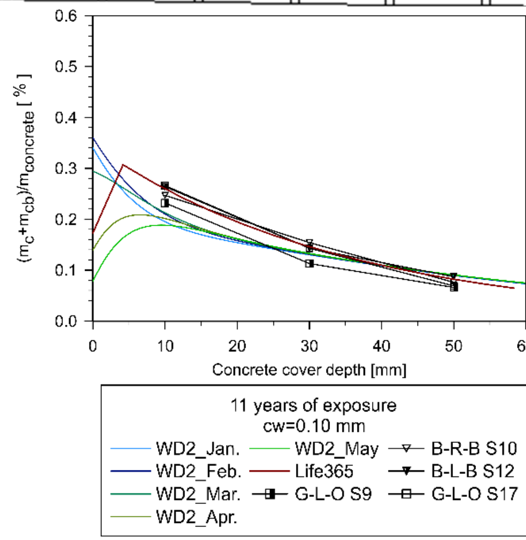
11 years of exposure

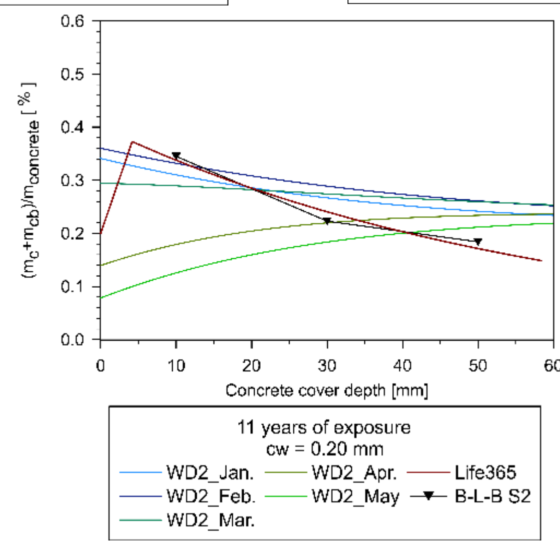
Exposure class: WD2

LEFT BRIDGE
TO ZAGREB









Kušter Marić et al. (2020)

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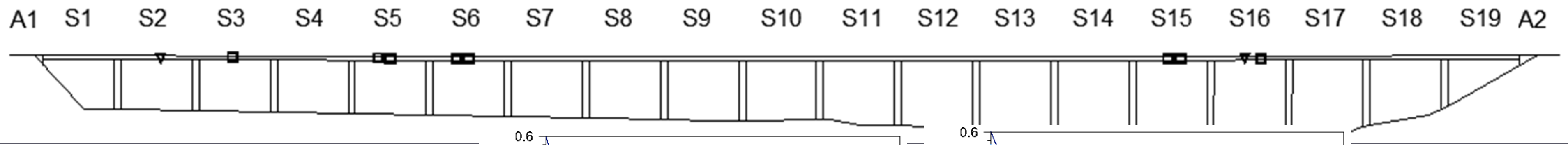
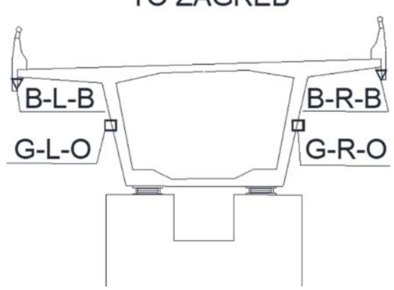
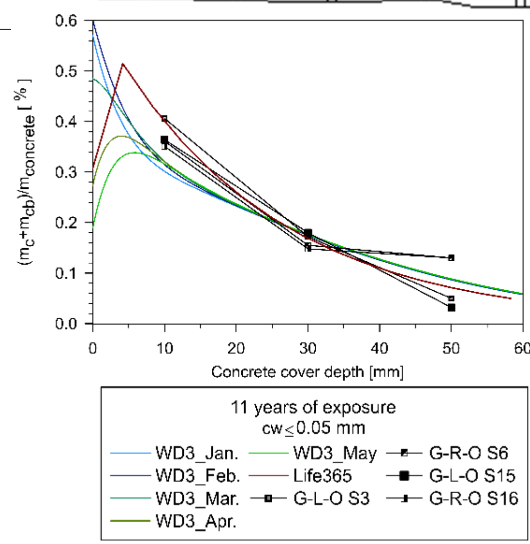


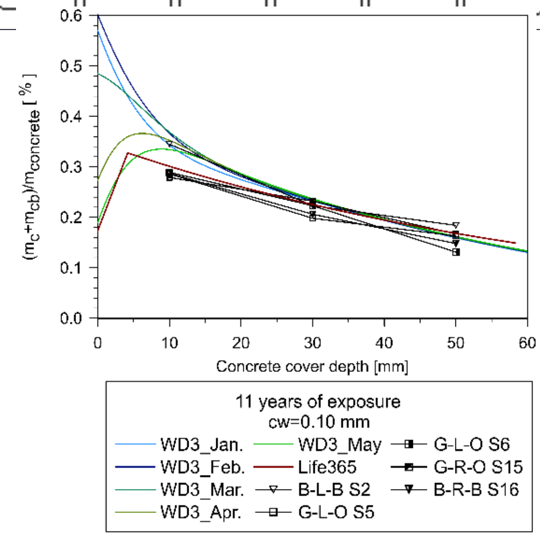
11 years of exposure

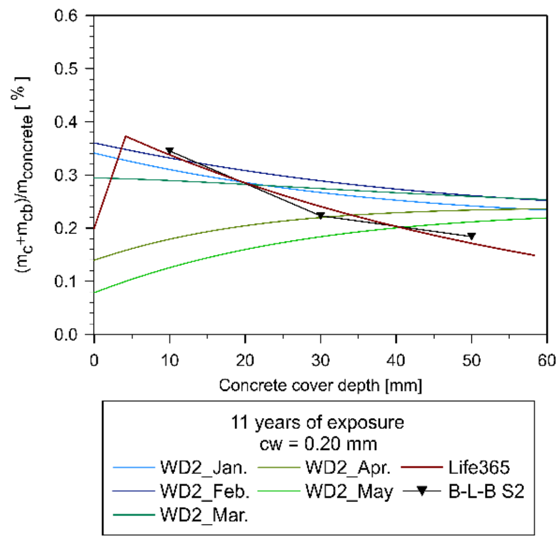
Exposure class: WD3

LEFT BRIDGE
TO ZAGREB









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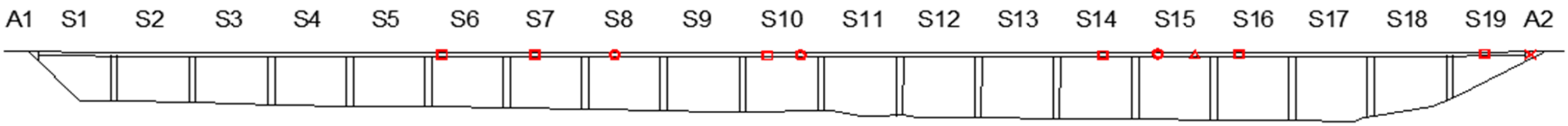
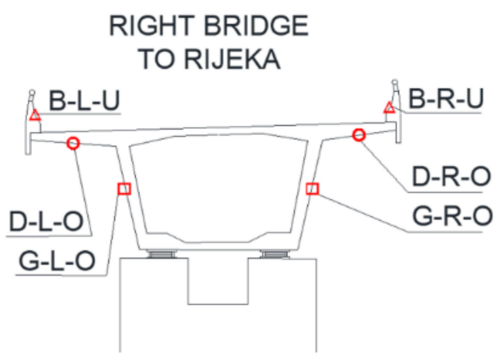
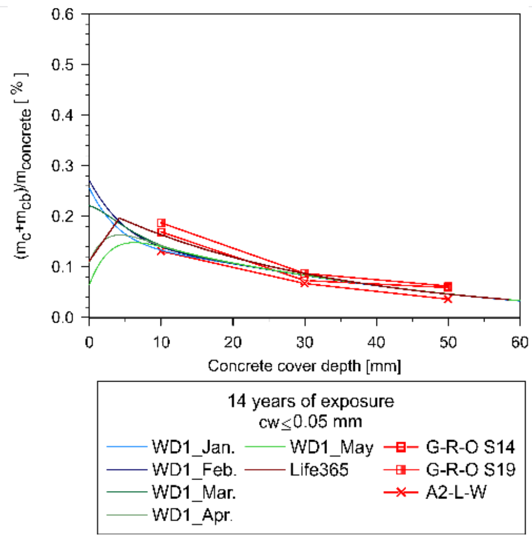
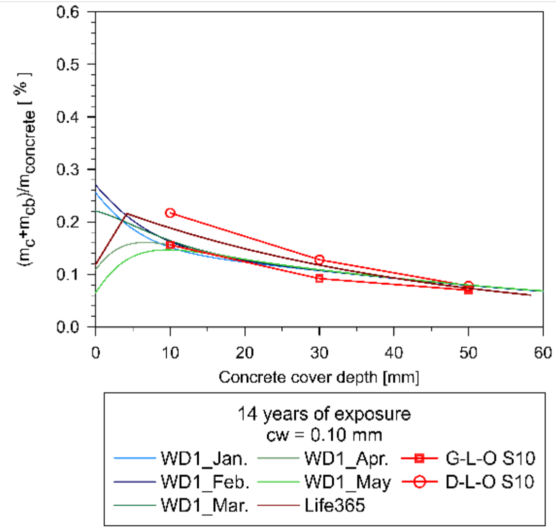


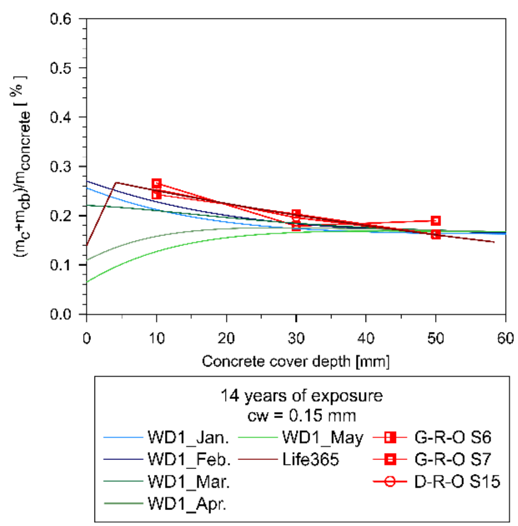
14 years of exposure

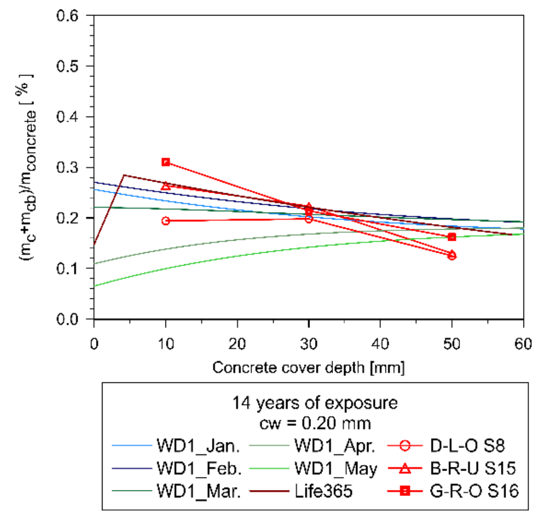
Exposure class: WD1











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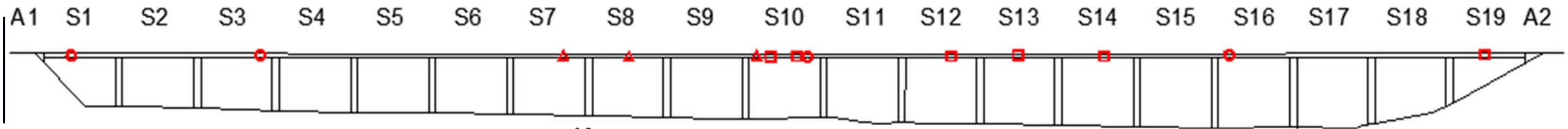
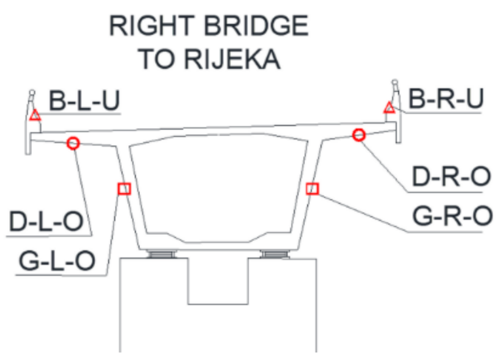
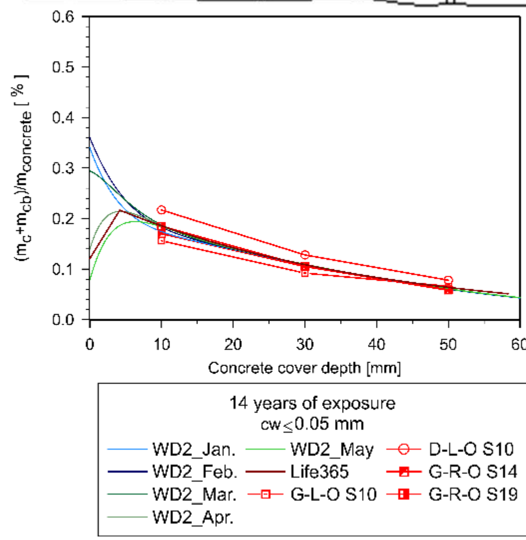
Comparison of numerical and measured chloride content

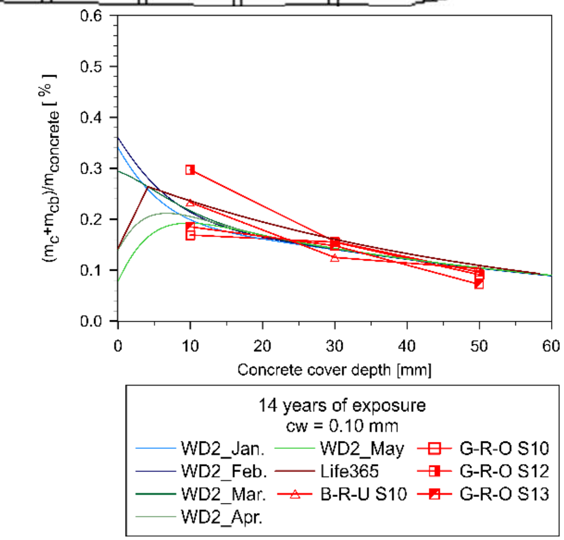


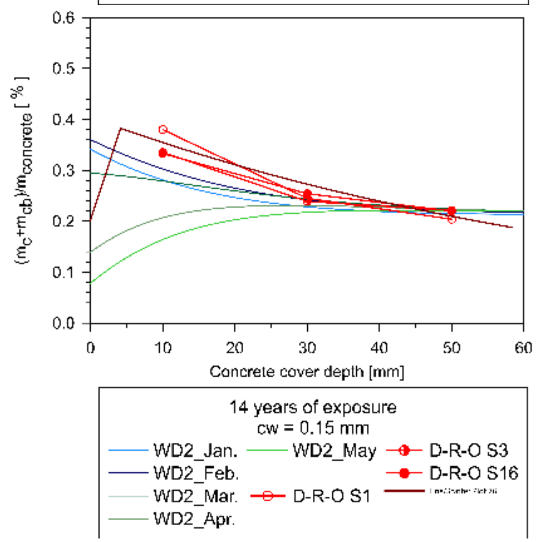
14 years of exposure

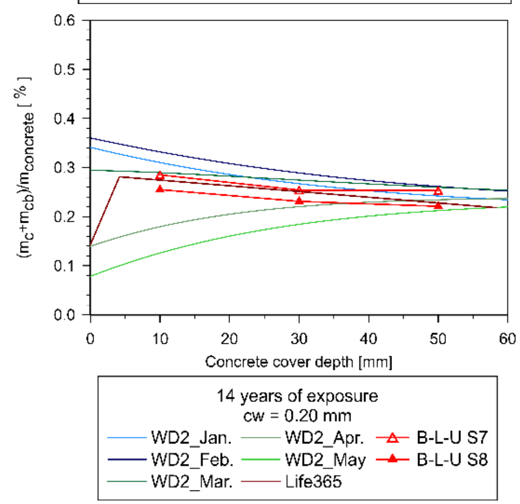
Exposure class: WD2











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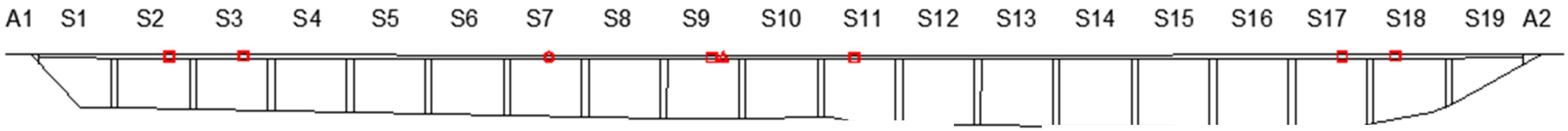
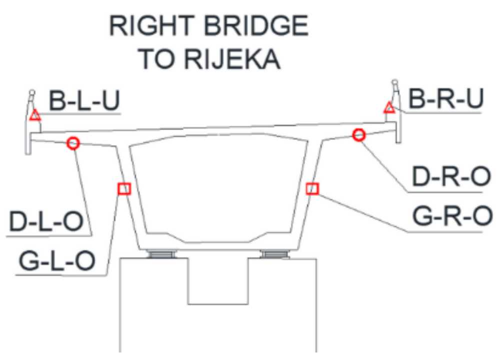
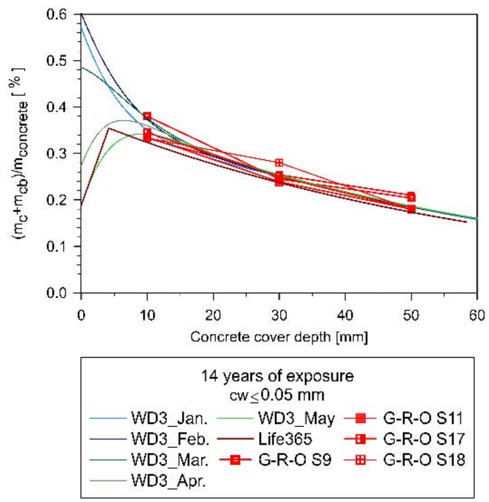
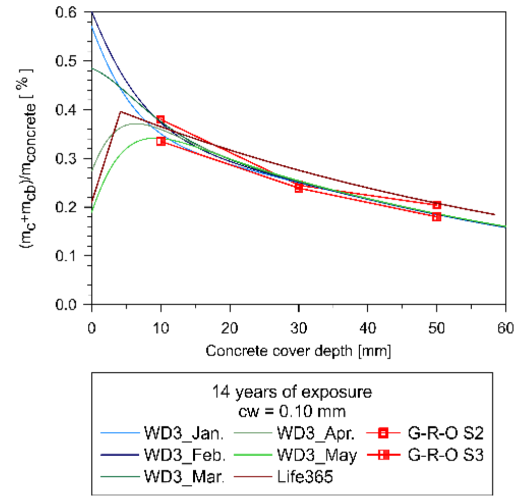


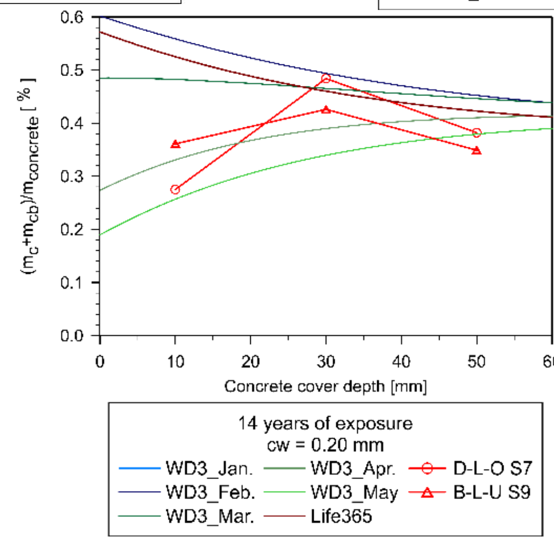
14 years of exposure

Exposure class: WD3









Kušter Marić et al. (2020)

Comperison of surface chloride contents and effective diffusivity

11 years of exposure

	Life365 Surface chloride content $(m_c+m_{cb})/m_{concrete}$ [%]				Life365 Chloride diffusion coeficient $[x10^{-11}\ m^2/s]$		3D CHTM Surface chloride content $(m_c+m_{cb})/m_{concrete}$ [%]				3D CHTM Chloride diffusion coeficient $[x10^{-11}\ m^2/s]$
	Minimum value	Mean value	Max. value	Standard deviation	Mean value	Standard deviation	Minimum value	Mean value	Max. value	Standard deviation	
WD1 cw ≤ 0.05 mm	0,060	0,168	0,240	0,069	180	24	0,0652	0,1219	0,2700	0,1141	6
WD1 cw = 0.10 mm	0,100	0,154	0,260	0,052	212	118	0,0652	0,1219	0,2700	0,1141	380
WD1 cw = 0.15 mm	0,170	0,170	0,170	0	830	0	0,0652	0,1219	0,2700	0,1141	4002
WD1 cw = 0.20 mm	0,110	0,133	0,155	0,023	2400	600	0,0652	0,1219	0,2700	0,1141	6000
WD2 cw ≤ 0.05 mm	0,135	0,205	0,275	0,057	99	29	0,0784	0,1604	0,3598	0,1528	6
WD2 cw = 0.10 mm	0,158	0,173	0,190	0,014	242	64	0,0784	0,1604	0,3598	0,1528	380
WD2 cw = 0.20 mm	0,200	0,200	0,200	0	700	0	0,0784	0,1604	0,3598	0,1528	6000
WD3 cw ≤ 0.05 mm	0,280	0,308	0,350	0,026	107	16	0,1897	0,2803	0,6012	0,2496	6
WD3 cw = 0.10 mm	0,155	0,174	0,210	0,017	956	437	0,1897	0,2803	0,6012	0,2496	380
WD3 cw = 0.15 mm	0,230	0,230	0,230	0	18000	0	0,1897	0,2803	0,6012	0,2496	4002

Surface chloride concentration and concrete diffusivity are determined separately for each chloride profile. (Life365)

Surface chloride concentration depends on exposure level (WD1-3), while difusivity depends on crack width (cw=0.0-0.2) (3D CHTM)

Comperison of surface chloride contents and effective diffusivity

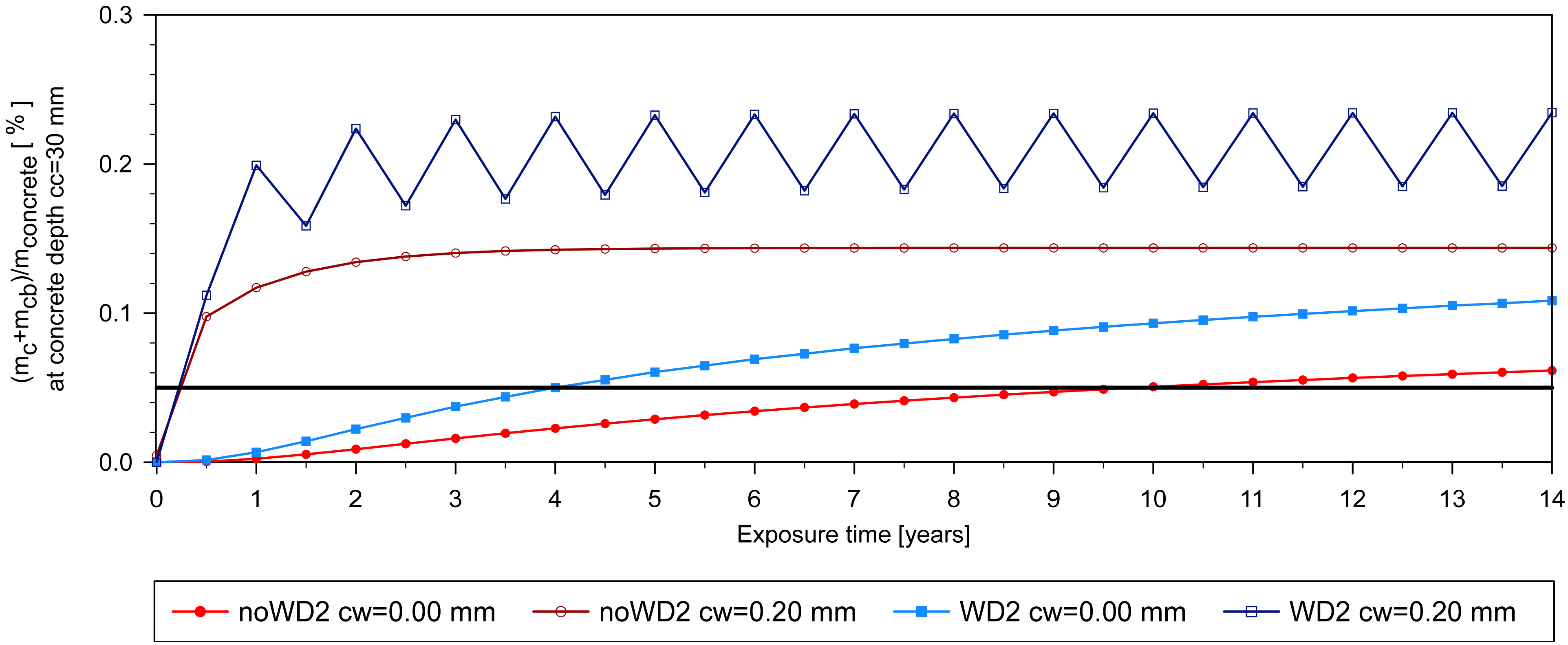
14 years of exposure

	Life365						3D CHTM				
	Surface chloride content $(m_c+m_{cb})/m_{concrete}$ [%]				Chloride diffusion coeficient [$x10^{-11}$ m^2/s]		Surface chloride content $(m_c+m_{cb})/m_{concrete}$ [%]				Chloride diffusion coeficient [$x10^{-11}$ m^2/s]
	Minimum value	Mean value	Max. value	Standard deviation	Mean value	Standard deviation	Minimum value	Mean value	Max. value	Standard deviation	
WD1 cw ≤ 0.05 mm	0,090	0,112	0,130	0,016	200	0	0,0652	0,1219	0,2700	0,1141	6
WD1 cw = 0.10 mm	0,102	0,119	0,135	0,017	365	15	0,0652	0,1219	0,2700	0,1141	380,626
WD1 cw = 0.15 mm	0,135	0,140	0,145	0,004	1700	294,39	0,0652	0,1219	0,2700	0,1141	95910
WD1 cw = 0.20 mm	0,110	0,148	0,180	0,029	2233	1958	0,0652	0,1219	0,2700	0,1141	6000
WD2 cw ≤ 0.05 mm	0,102	0,121	0,135	0,013	282,5	83,179	0,0784	0,1604	0,3598	0,1528	6
WD2 cw = 0.10 mm	0,105	0,143	0,200	0,037	542,5	297,35	0,0784	0,1604	0,3598	0,1528	380,626
WD2 cw = 0.15 mm	0,185	0,202	0,235	0,024	1183	447,83	0,0784	0,1604	0,3598	0,1528	95910
WD2 cw = 0.20 mm	0,137	0,144	0,153	0,009	30000	0	0,0784	0,1604	0,3598	0,1528	6000
WD3 cw ≤ 0.05 mm	0,155	0,189	0,235	0,029	832,5	403,32	0,1897	0,2803	0,6012	0,2496	6
WD3 cw = 0.10 mm	0,185	0,210	0,235	0,025	1025	475	0,1897	0,2803	0,6012	0,2496	380,626
WD3 cw = 0.15 mm	0,260	0,330	0,400	0,070	2975	2025	0,1897	0,2803	0,6012	0,2496	95910

Surface chloride concentration and concrete diffusivity are determined separately for each chloride profile.

Surface chloride concentration depends on exposure level (WD1-3), while difusivity depends on crack width (cw=0.0-0.2)

Impact of wetting-drying cycles and concrete crack on chloride content on the reinforcement level



Kušter Marić et al. (2020)

CONCLUSION

1

- 3D CHTM model and Life-365 are capable to realistically predict chloride ingress in concrete after long time exposure to de-icing salts

2

- Wetting – drying cycles and concrete cracks result in higher chloride content and faster reinforcement depassivation

3

- Variability of climate parameters, such as relative humidity and temperature, have important impact on service life prediction.

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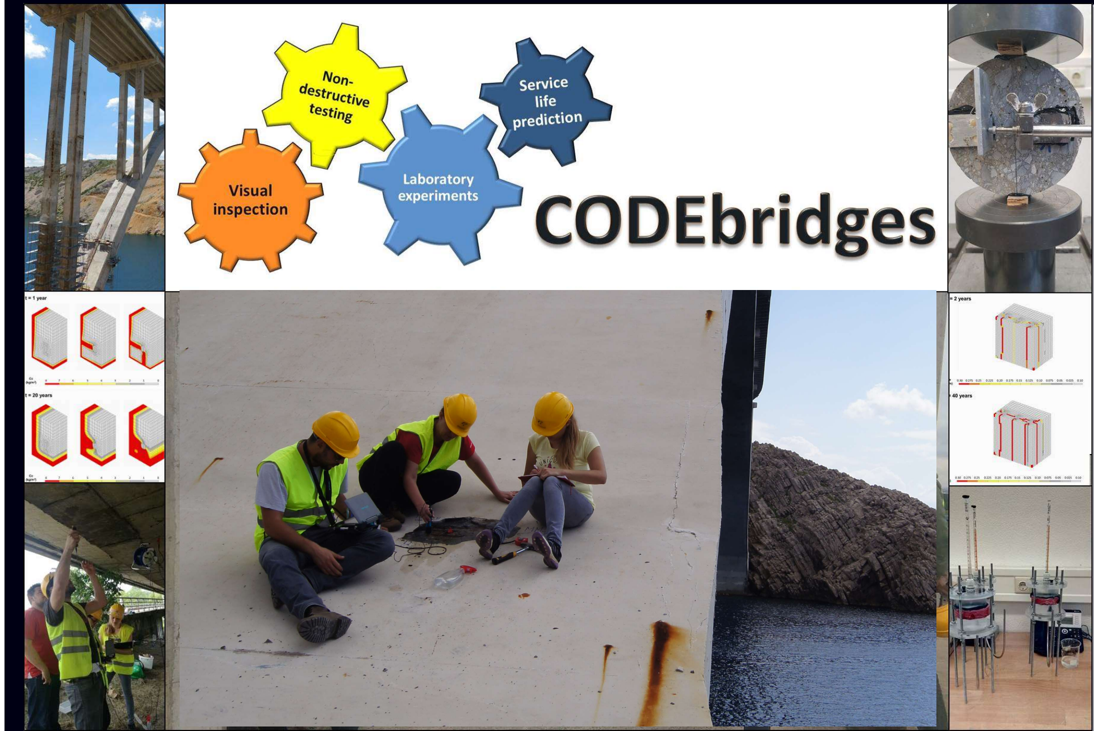

CROCANDY

Durability of reinforced concrete structures - Croatian and Canadian practices

UNIVERSITY OF ZAGREB
FACULTY OF CIVIL ENGINEERING

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Thank you for your attention!

Evaluation of chloride-ingress models on concrete bridge exposed to deicing salts

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