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# Durability of engineered concrete barriers under final disposal conditions (Aalto & VTT)

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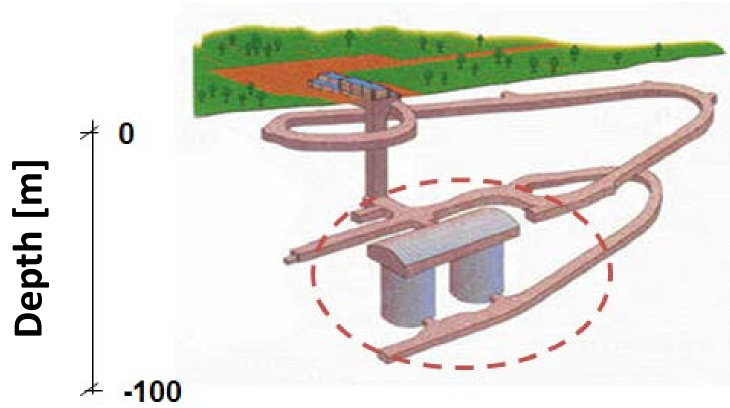
# Content of the Presentation

I. Background
II. Modelling approach
III. Materials and experimental work
IV. Simulation
V. Concluding remarks

# Background of the research

Layout of the low and medium activity waste repository in Finland:




- The safety of the repository is partly ensured by multiple concrete barriers which shall be serviceable more than 500 years
- Modern type concrete has only been used relative short period of time and experimental evidence of its long-term behaviour is not available

# Ageing of reinforced concrete under disposal conditions

Aerial carbonation of concrete is the main ageing mechanism during the operating phase with assumed length of 10 - 100 years

Physical and chemical ageing of reinforced concrete will take place during the post-closure period when the structure will be submerged

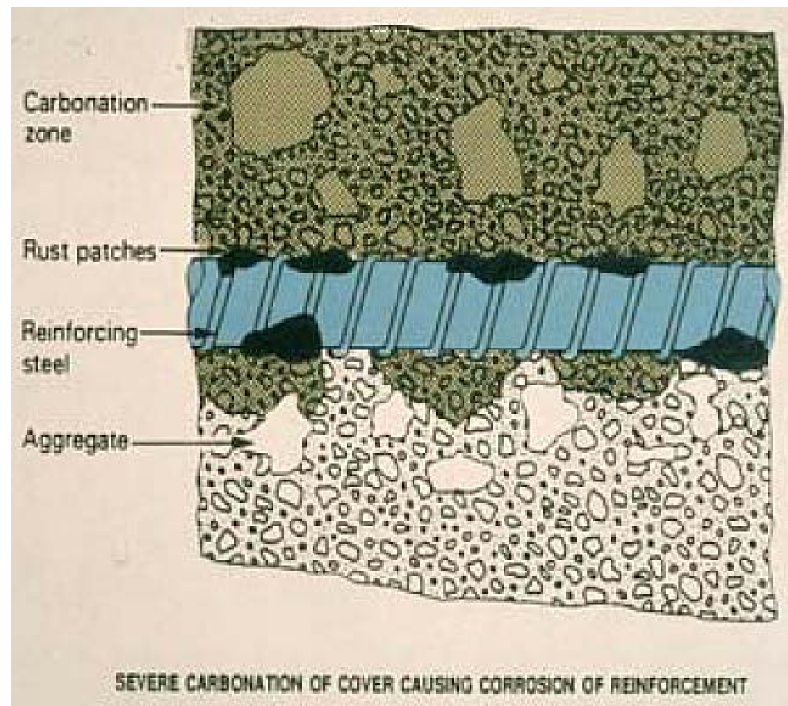
- Initiation of steel reinforcement corrosion
- Disintegration of concrete

# Aerial carbonation during operating phase

- Aerial carbonation of concrete is mainly happening when atmospheric carbon dioxide diffuses into unsaturated concrete and dissolves in the pore water reacting in the presence of water with dissolved calcium hydroxide to form calcium carbonate

$$Ca(OH)_2 + CO_2 \xrightarrow{H_2O} CaCO_3 + H_2O$$

- pH of the pore solution in the carbonated zone drops and reinforcing steel becomes de-passivated and might corrode

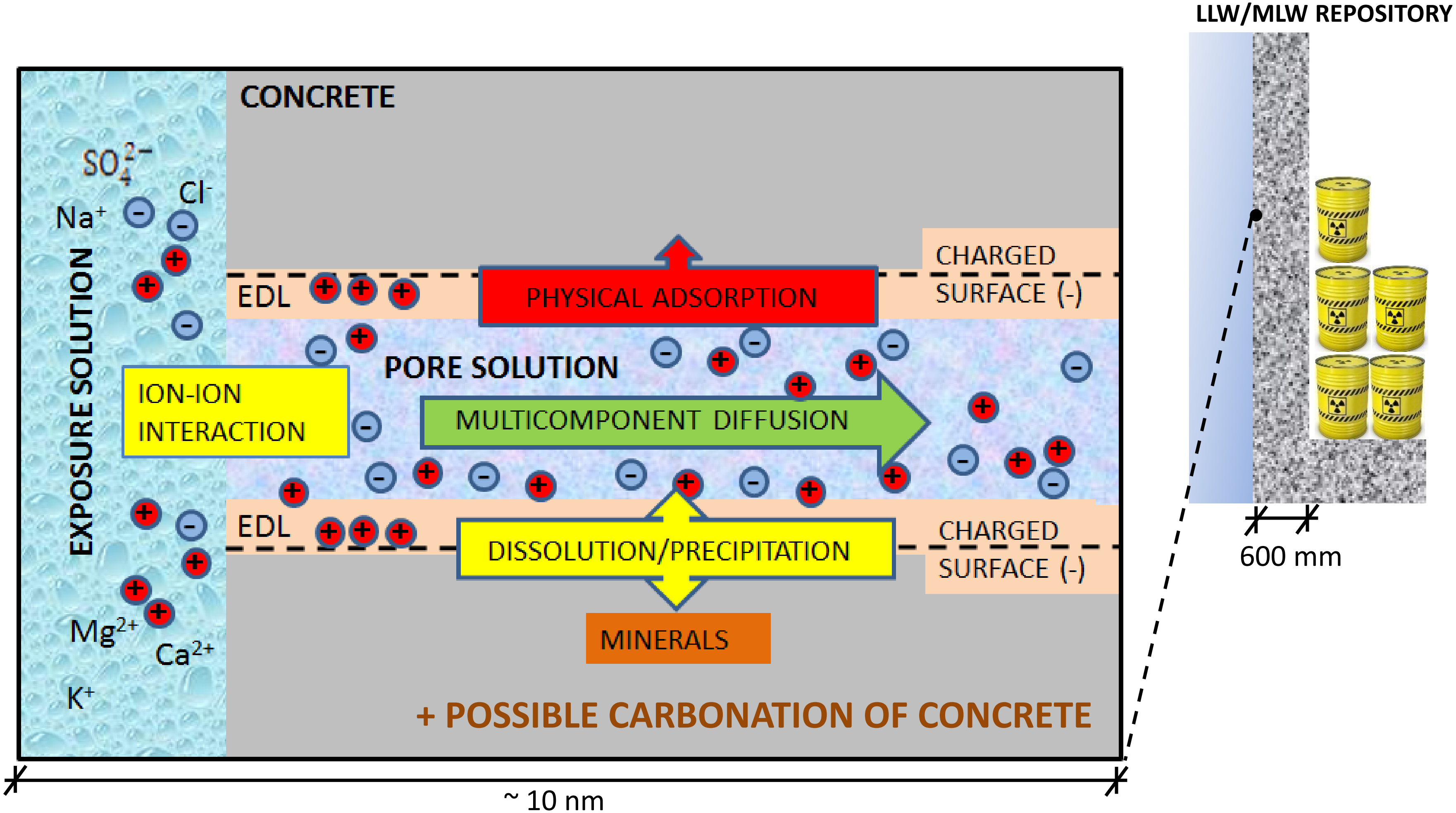



*D. Hooton (2010)*

# Physical and chemical ageing during post-closure period

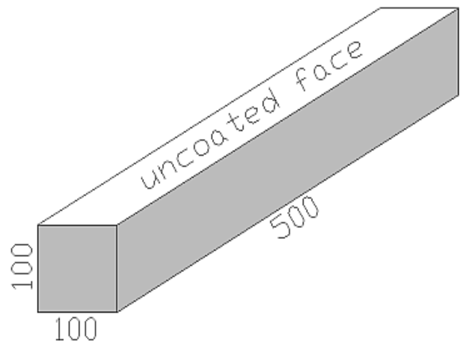
- After closing the repository, groundwater will gradually fill the disposal zone exposing concrete to aggressive ions
- The presence of chlorides can be evaluated as being the main concern for the steel reinforcement corrosion
  - The chlorides usually penetrate into the concrete accompanied by other ions present such as sulphate and magnesium which have their own durability impact
- Leaching or precipitation of cement hydrates may lead to disintegration of concrete and accelerate the ingress of aggressive species
- $CO_2$ can also dissolve in the water surrounding concrete during post-closure period

# Schematic view of the chemical and physical processes in saturated concrete



# Concrete specimens

Concrete specimens being under the exposure tests ([1] and submerged since year **1998**, were used in the verification of the model.




| Mix [kg/m$^3$] | Cement type | CEM | SF | BFS | Aggr | Wat | w/b |
|---|---|---|---|---|---|---|---|
| **B1** | CEM I 42.5SR | 453 | - | - | 1811 | 159 | 0.350 |
| **B2** | CEM I 42.5SR | 373 | - | - | 1867 | 159 | 0.425 |
| **B3** | CEM I 42.5SR | 319 | - | - | 1918 | 160 | 0.500 |
| **B4** | CEM IIA 42.5 | 402 | 44 | - | 1797 | 157 | 0.350 |
| **B5** | CEM IIA 42.5 | 334 | 37 | - | 1857 | 158 | 0.425 |
| **B6** | CEM IIA 42.5 | 286 | 32 | - | 1907 | 158 | 0.500 |
| **B7** | CEM I 42.5R | 89 | 23 | 336 | 1787 | 159 | 0.350 |
| **B8** | CEM I 42.5R | 74 | 19 | 279 | 1862 | 158 | 0.425 |
| **B9** | CEM I 42.5R | 63 | 16 | 238 | 1913 | 159 | 0.500 |

| | Composition [mg/l] | | |
|---|---|---|---|
| Solution | $Cl^-$ | $SO_4^{2-}$ | $Mg^{2+}$ |
| **L1** | - | 20 | - |
| **L2** | - | 500 | - |
| **L3** | - | 1000 | - |
| **L4** | 50 | - | - |
| **L5** | 1000 | - | - |
| **L6** | 10000 | - | - |
| **L7** | 50 | 20 | 5 |
| **L8** | 1000 | 500 | 100 |
| **L9** | 10000 | 1000 | 300 |

*([1] A. Ipatti, Concrete long-term durability under final disposal conditions – laboratory and field tests 1997 – 2003, TVO, VLJ-4/04, 2004*

# Laboratory experiments

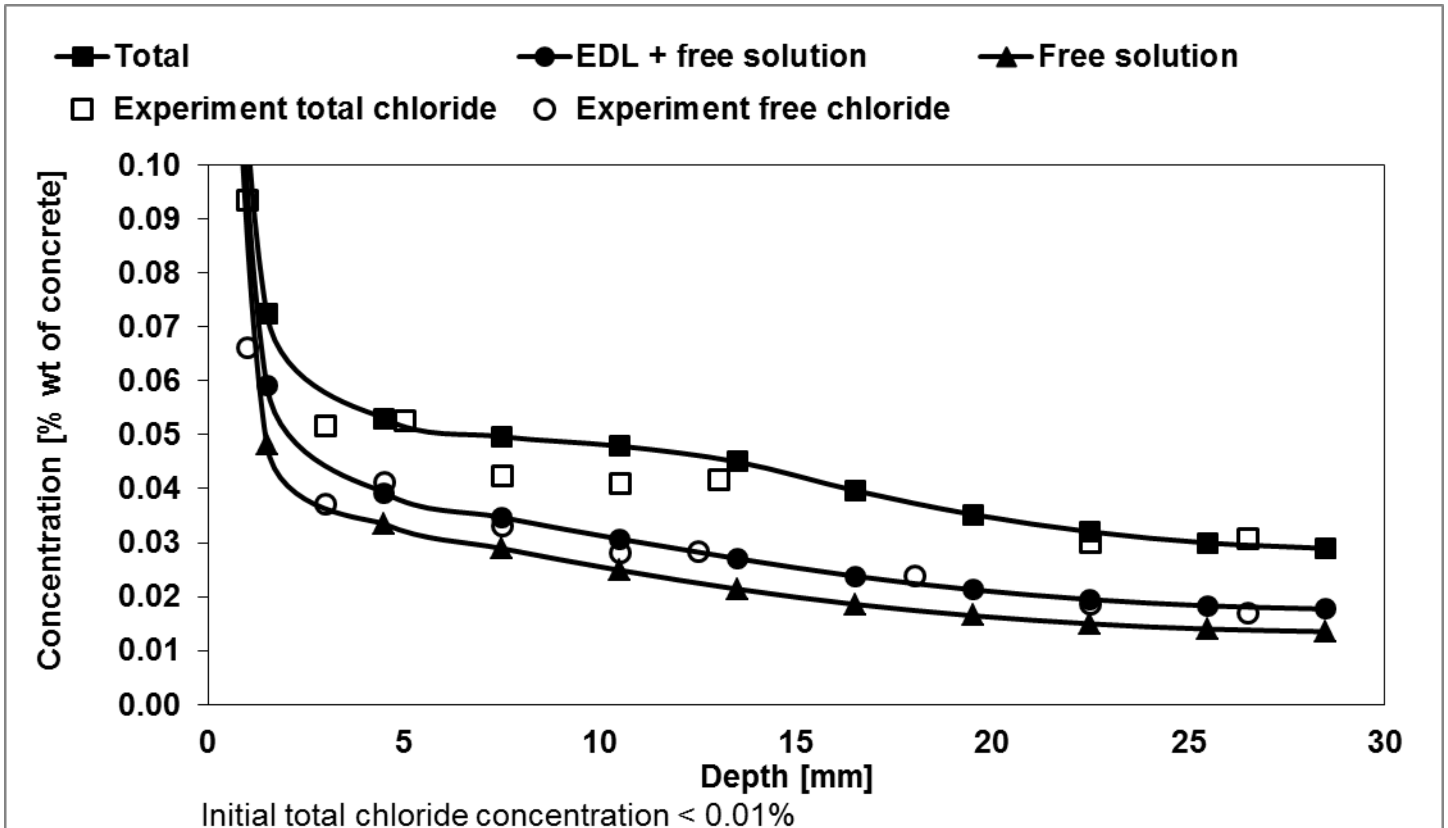
- A large variety of laboratory tests were carried out by VTT ([1]
  - Penetration profiles of aggressive components (titrations, ICP analysis method)
  - Microstructure and elemental distribution of the concretes (SEM/EDS)
  - Mineral compositions and hydration of the concretes (XRD + TG)
  - Water uptake and porosity of the concretes (capillary water uptake test)

- Some detailed tests were also made in Aalto University
  - Pore solution composition (pore solution extraction and ICP analysis)
  - Pore sizes distribution and detailed pore structure (MIP and nitrogen adsorption)
  - Tortuosity of the pore structure (RCM for chlorides)
  - pH-value tests for concrete

*([1] Vesikari E, Koskinen P (2012) Durability of Concrete Barriers in Final Depositories of Nuclear Waste. Research report VTT-R-01185-12*

# Simulation for the case B2/L9

Chloride concentrations after exposure tests of 13 years; experiments vs. model

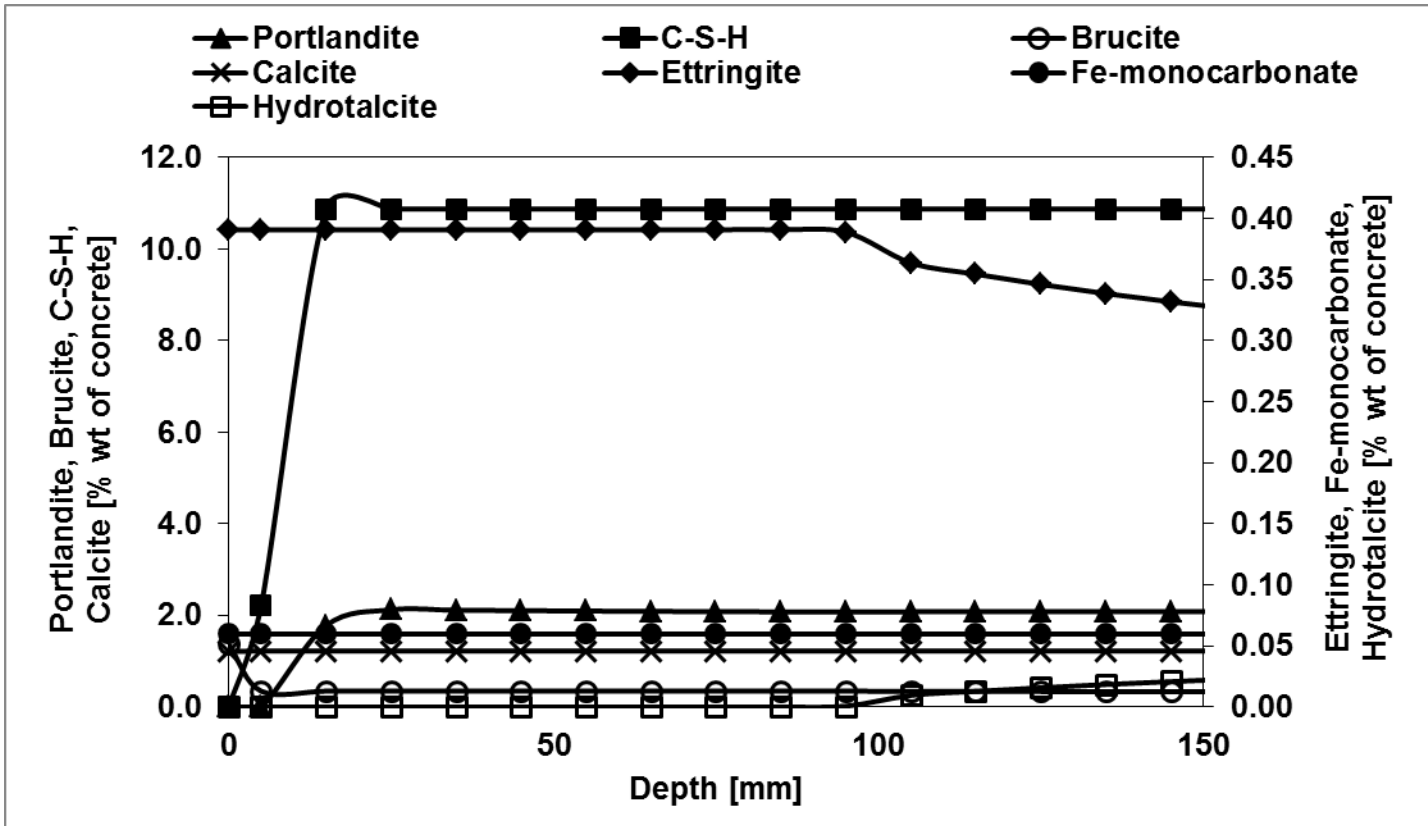



*Calculated with PHREEQC*


*Kari O P, Elakneswaran Y, Nawa T, Puttonen J, "A model for a long-term diffusion of multispecies in concrete based on ion–cement-hydrate interaction", Journal of Materials Science, doi: 10.1007/s10853-013-7239-3*

# Simulation for the case B2/L9

Solid phase distribution after 500 years' exposure

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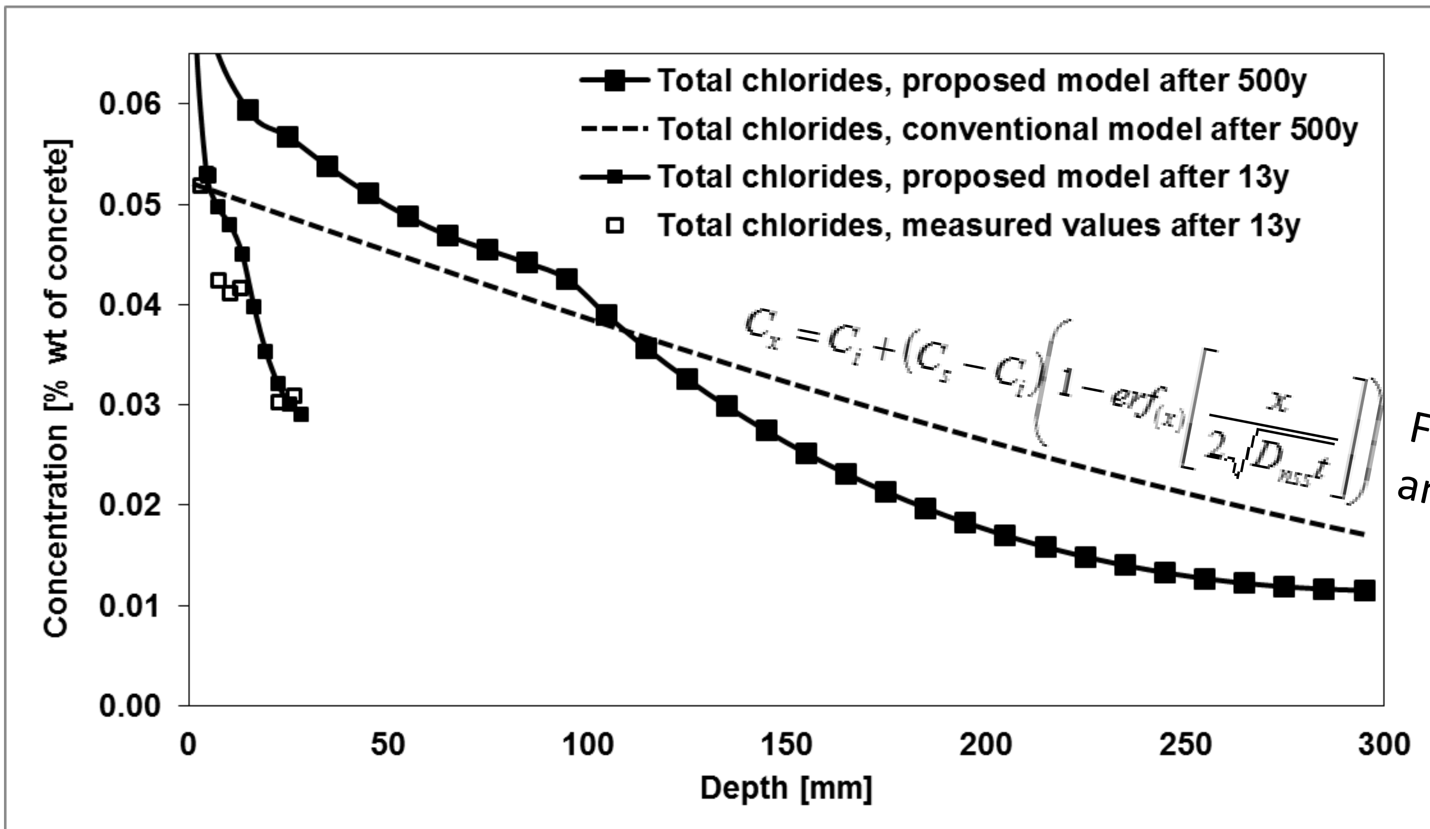
# Simulation for the case B2/L9

Total chloride concentration after exposure of 500 years according to the proposed and conventional model vs. the situation after 13 years.

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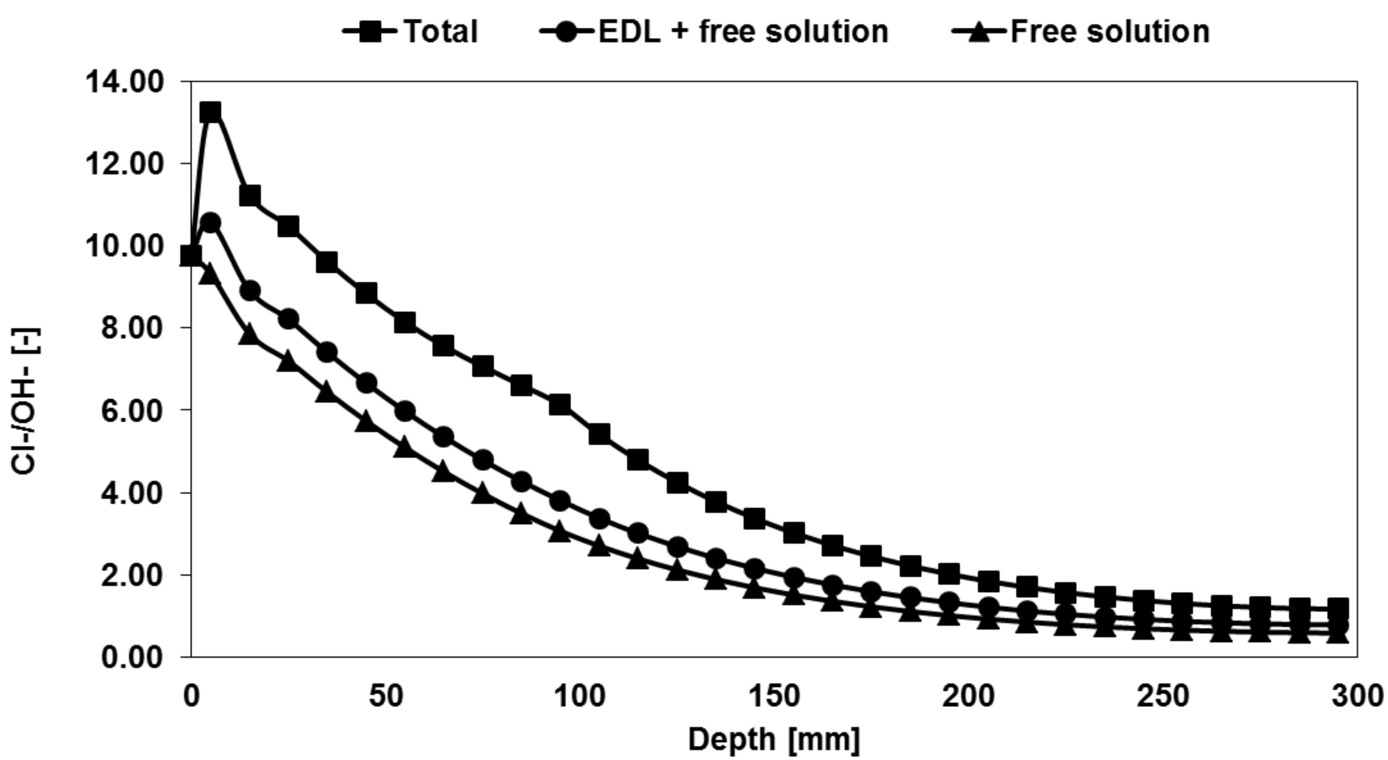
# Simulation for the case B2/L9

$Cl^-/OH^-$ -relation after 500 hundreds years of exposure. Corrosion of ordinary steel reinforcement is generally assumed to initiate when $Cl^-/OH^-$ is between 0.3 – 6.

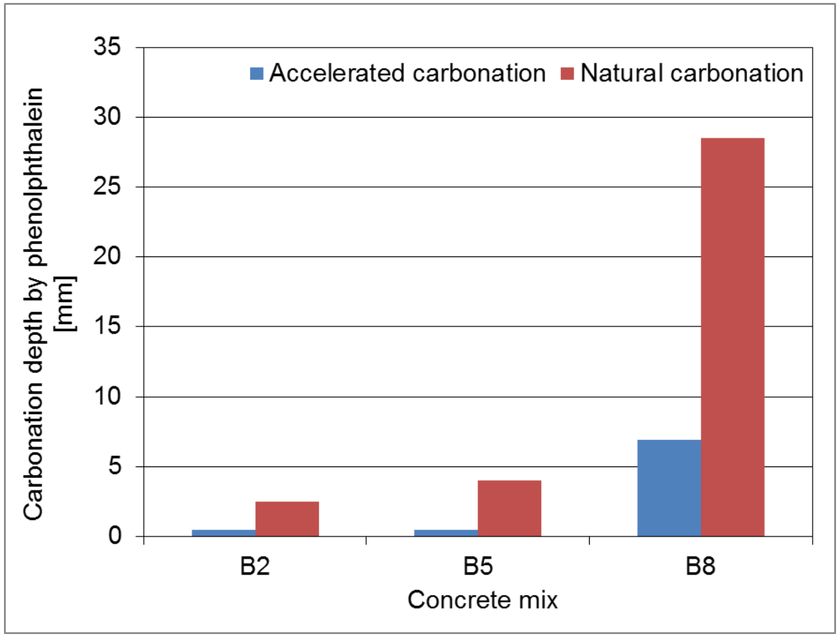



*Calculated with PHREEQC*

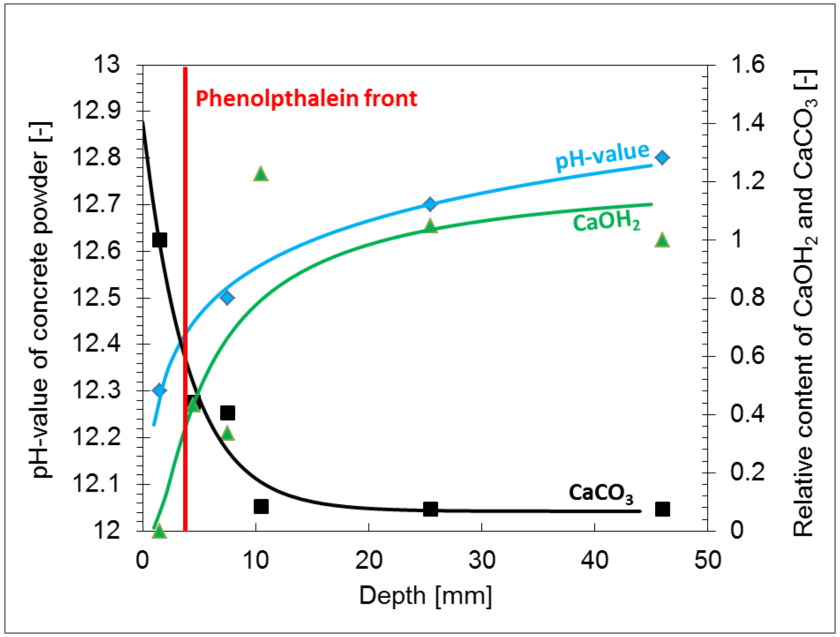
*Kari O P, Elakneswaran Y, Nawa T, Puttonen J, "A model for a long-term diffusion of multispecies in concrete based on ion–cement-hydrate interaction", Journal of Materials Science, doi: 10.1007/s10853-013-7239-3*

# Complexity of concrete carbonation

Measured aerial concrete carbonation by phenolphthalein after 12 years; Natural conditions and the estimation through accelerated laboratory test




Main cement hydrates and pH-value of the case B2 measured after 12 years being under natural conditions (simulations corresponded well with the results)




-> prediction of concrete carbonation in the long-term needs proper experimental results and detailed analysis

# Concluding remarks

- A developed thermodynamic model showed good correlation with large variety of long-term experimental data of SRPC -concretes
- Continuous time-dependent changes of concrete shall be considered when evaluating ageing of reinforced concrete
- The case-specific long-term laboratory tests are important for ageing management of concrete structures under disposal conditions
- Concrete carbonation and chloride threshold content need more investigation