

Reinforcement bars corrosion in a carbonated concrete

B. Chinè¹, R. Jimenez S.¹ and R. Cuevas K.²

¹ School of Materials Science and Engineering, Costa Rica Institute of Technology, Cartago, Costa Rica

² School of Construction Engineering, Costa Rica Institute of Technology, Cartago, Costa Rica

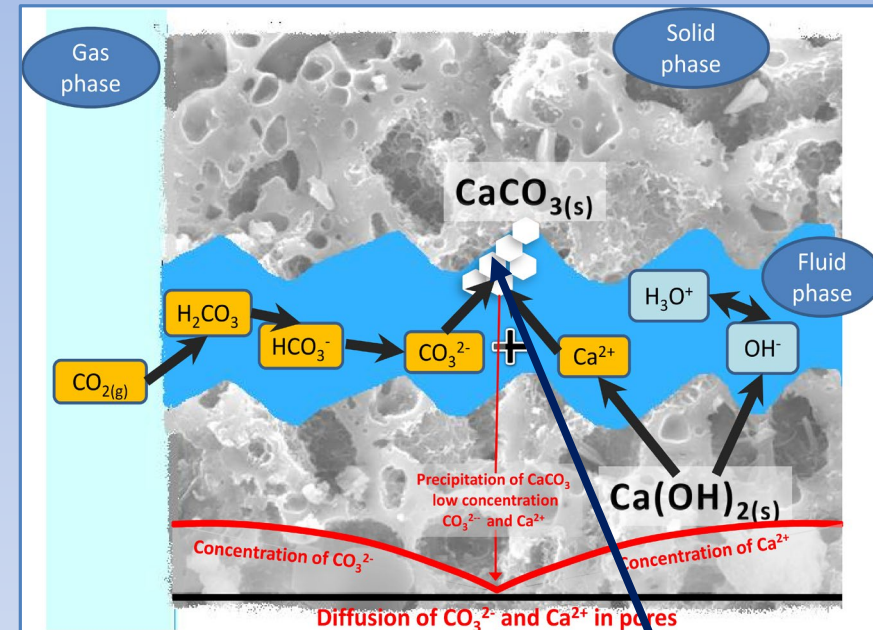
bchine@itcr.ac.cr

Presentation overview

- **Concrete carbonation and reinforcement bars corrosion**
- **Experimental work**
- **Computational model**
- **Solution with Comsol Multiphysics®**
- **Numerical results**
- **Conclusions**

Concrete carbonation

- CO_2 permeates the porous and fractured structure of concrete and establishes conditions of concrete degradation.
 - The value of the concrete carbonation enhances the corrosion around the reinforcing bar.
- ↕
- The corrosive process can break the passivation layer protecting the steel, when the alkalinity of the aqueous solution (electrolyte) in the pores of the concrete decreases due to carbonation.
- ➔
- It promotes deterioration of the mechanical properties of the material and finally of the structure.



calcium carbonate

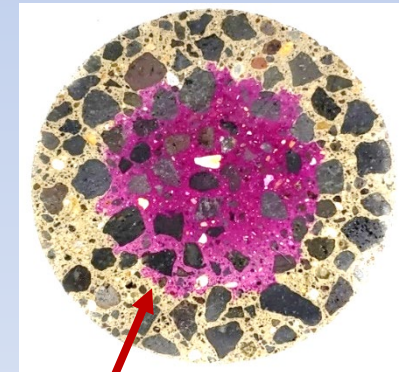
Experimental work: concrete carbonation

- Using an accelerated carbonation chamber, we carried out testing on cylindrical concrete samples reinforced with four steel bars.
 - Experimental kinetics data of the electrochemical electrode reactions will reflect the carbonation front progress.
- ↓
- Therefore, the experimental work considered electrochemical measurements to characterize the corrosion mechanism of the metal elements.



Material	Weight (kg)
Hydraulic cement (MP/A-28)	381.927
Sand (wet)	687.31
Gravel (wet)	907.12
Water	197.45

Water to binder w/c ratio is 0.52, but the effective value is 0.57, considering the humidity of the material.

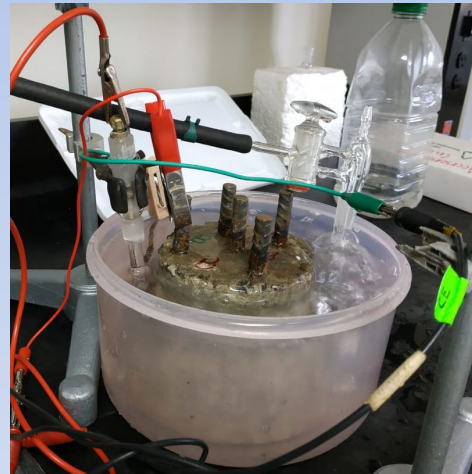


Carbonation depth (18 ± 1 mm) in the sample of concrete, after 33 days of accelerated carbonation

Experimental work: reinforcement bars corrosion

Polarization test for four steel bars placed at different distance from the outer surface of the sample

Experimental kinetics data of the electrochemical electrode reaction reflecting the carbonation front progress



We measured values of corrosion potential, corrosion current density, anodic, and cathodic slopes of the **Tafel curve**

Distance: 5 mm			
E _{corr} (V)	i _{corr} (A/cm ²)	ba (V/dec)	bc (V/dec)
-0.6507	9.1468E-06	0.92964	-0.91109
Distance: 10 mm			
E _{corr} (V)	i _{corr} (A/cm ²)	ba (V/dec)	bc (V/dec)
-0.6051	7.5005E-06	0.88559	-0.82915
Distance: 15 mm			
E _{corr} (V)	i _{corr} (A/cm ²)	ba (V/dec)	bc (V/dec)
-0.5685	4.0430E-06	0.64922	-0.60148
Distance: 20 mm			
E _{corr} (V)	i _{corr} (A/cm ²)	ba (V/dec)	bc (V/dec)
-0.5239	6.4684E-06	1.0871	-0.8971

Experimental work: reinforcement bars corrosion



The values of **exchange currents** are computed and then used to simulate the corrosion of four reinforcing bars

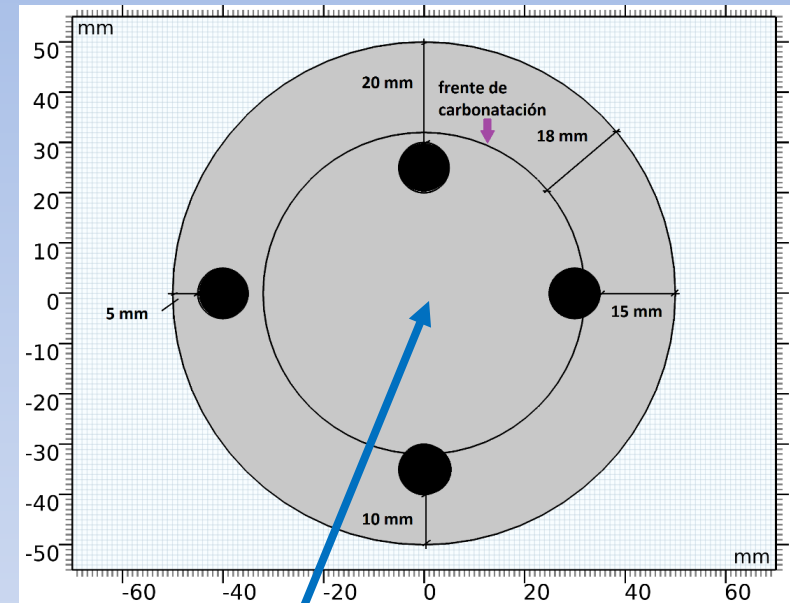
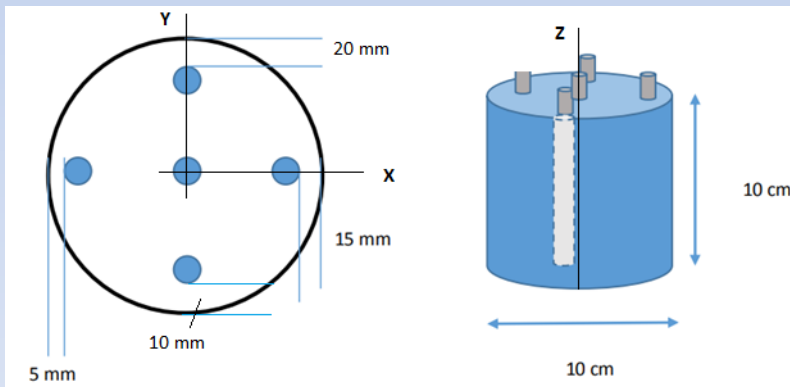
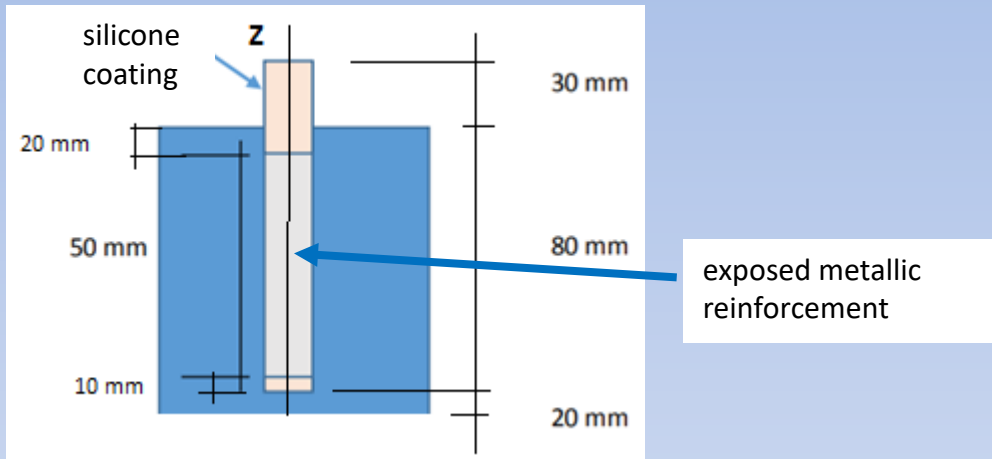


These experimental data are then introduced in Comsol Multiphysics® 6.1 to model the corrosion of the reinforcing metal under steady state conditions



Distance: 5 mm	
i_o (Fe oxidation) (A/cm ²)	i_o (O ₂ reduction) (A/cm ²)
0.1017 E-04	0.1308 E-06
Distance: 10 mm	
i_o (Fe oxidation) (A/cm ²)	i_o (O ₂ reduction) (A/cm ²)
0.0744 E-04	0.0800 E-06
Distance: 15 mm	
i_o (Fe oxidation) (A/cm ²)	i_o (O ₂ reduction) (A/cm ²)
0.0351 E-04	0.0089 E-06
Distance: 20 mm	
i_o (Fe oxidation) (A/cm ²)	i_o (O ₂ reduction) (A/cm ²)
0.0541 E-04	0.1199 E-06

Computational model: geometry



The central metallic bar is excluded

Schematic and dimensions of the reinforced concrete sample

Computational model: hypothesis

- concrete is a porous medium not completely saturated with water, where the carbonation phenomenon modifies the passivation state of the metallic reinforcement;
- the oxidation-reduction process is modeled by oxidation of Fe and reduction of O_2 on the whole surface of the metallic bars (uniform corrosion by carbonation);
- the atmospheric O_2 surrounding the concrete diffuses in the gas phase of the pores, towards the metal surfaces;
- the electrochemical corrosion reactions are controlled by the O_2 concentration in proximity of the bars, with sufficient water;
- the oxidized material of the reinforcement and its volumetric changes are neglected;
- the corrosion phenomenon is modeled under steady-state conditions.

Solution with Comsol Multiphysics 6.1[®]

- The **electrochemical mechanisms** of the reinforced concrete is defined using the Second Current Distribution of the Corrosion Module.
- The computation of the **oxygen diffusion is** developed with the Transport of Dilute Species interface of the Chemical Reaction Engineering Module.
- Electrode Surface Coupling introduces a flux boundary condition based on current densities and stoichiometric coefficient according to Faraday's law.

Boundary conditions and other magnitudes for O₂ diffusion

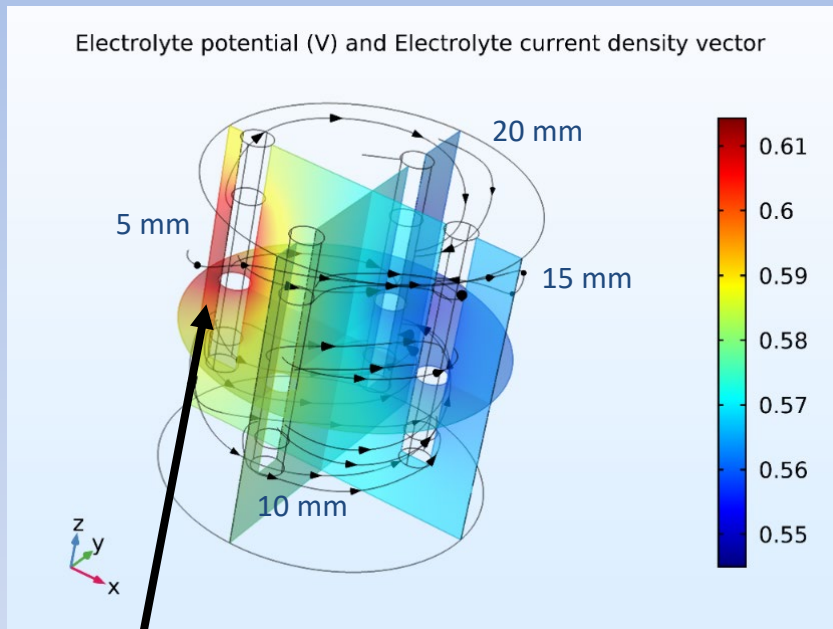
- For gaseous O₂, a concentration of 8.58 mol/m³ is set at the boundaries (partial volume of oxygen of 21% in the carbonation chamber).
- Except for the exposed metal surfaces, all other walls are considered impermeable to O₂.
- Using a correlation of literature, the porous medium is assigned a porosity of 0.32 and a water saturation equal to 0.27 (water cement ratio of 0.57 and relative humidity of 65% in the carbonation chamber).
- It is assumed that O₂ moves in the gas phase of the pores with an effective transport coefficient of 2.5×10^{-8} m²/s, as a function of porosity and relative humidity.
- The initial O₂ concentration in the computational domain is also equal to 8.58 mol/m³.

Boundary conditions and other magnitudes for corrosion mechanism

- Excluding the exposed areas of the metal, all other surfaces are electrically insulated, both in the electrolyte and in the electrode.
- Concrete is modeled as an electrolytic medium with an effective electrical conductivity of 0.005 S/m.
- The calculation of the electric currents inside the metal is neglected since its electrical conductivity is much greater than that of the electrolyte.
- The experimental values of i_0 , b_a , and b_c are used to describe the electrochemical kinetics of the metal/concrete interfaces.

Numerical results

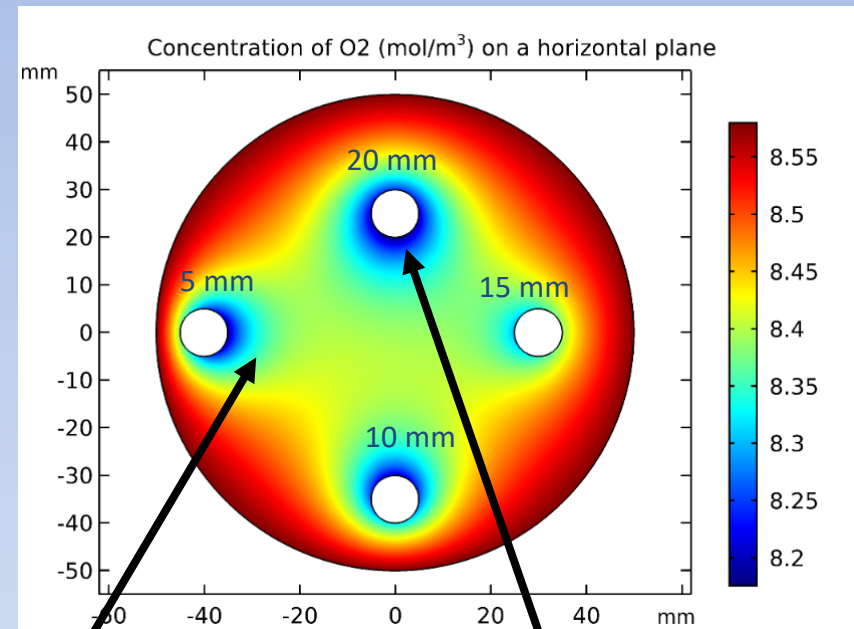
Electrolyte potential (V) and Electrolyte current density vector



The concrete (electrolyte), in the regions where the anodic reactions are more intense, presents a more positive electrical potential than the concrete of the regions where these are less intense

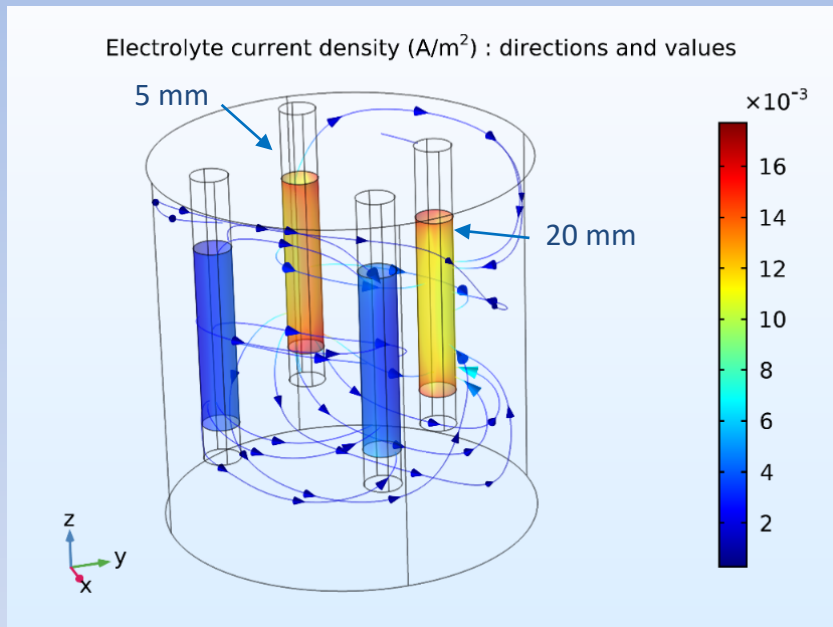
The decrease in O_2 is evident in the area near the metal, in the regions facing the centre of the cylinder (consumption of O_2 in the reduction reactions, a sink modeled by the Faraday's law)

plane at $z = 50$ mm

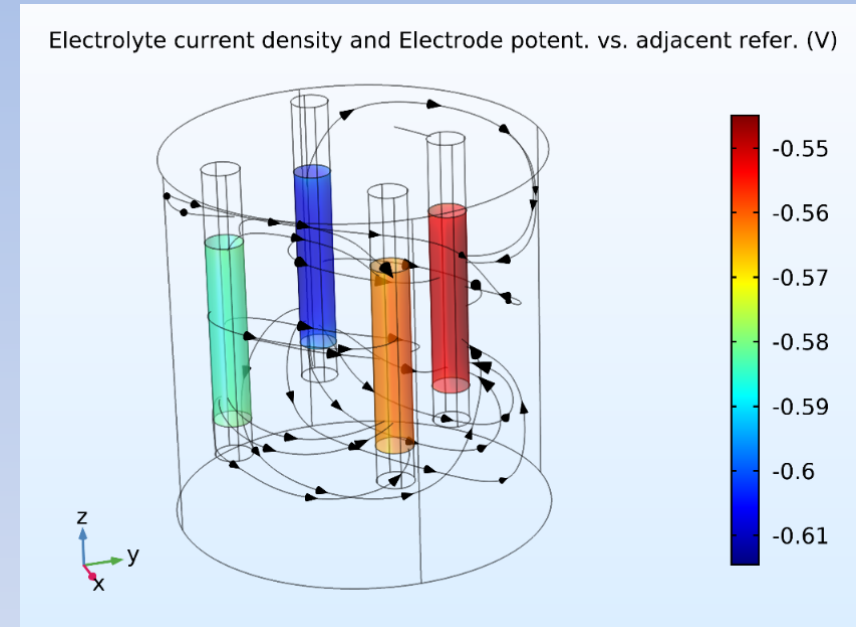


For the reinforcement placed 20 mm, the O_2 is even lower, since this electrode is more distant from the periphery, where the boundary concentration is fixed

Numerical results



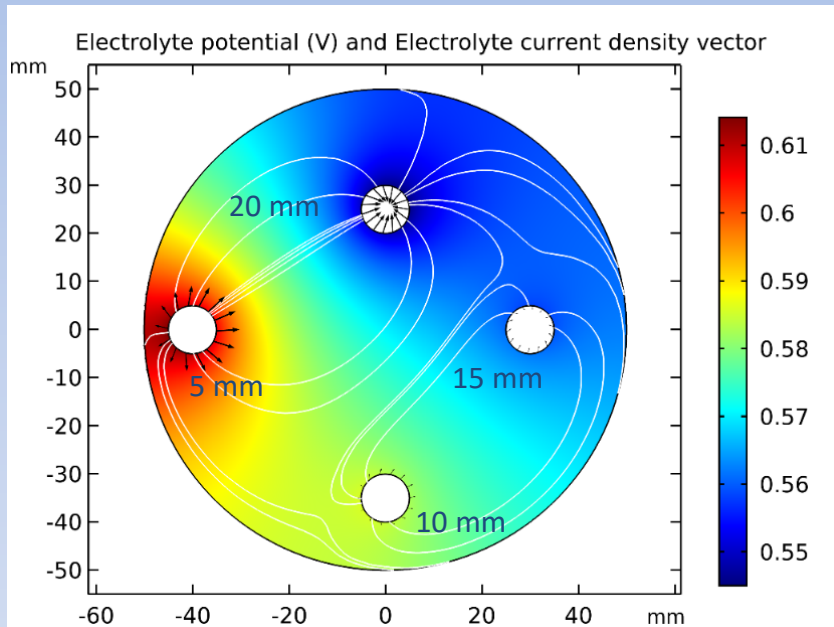
In proximity to the bar positioned 5 mm, the electric current is more intense and the O_2 concentration is low, due to the reduction reactions.



The electrolyte current density lines arise in the regions where Fe oxidation is most intense, i.e. in the outermost rods of the carbonated concrete.

Numerical results

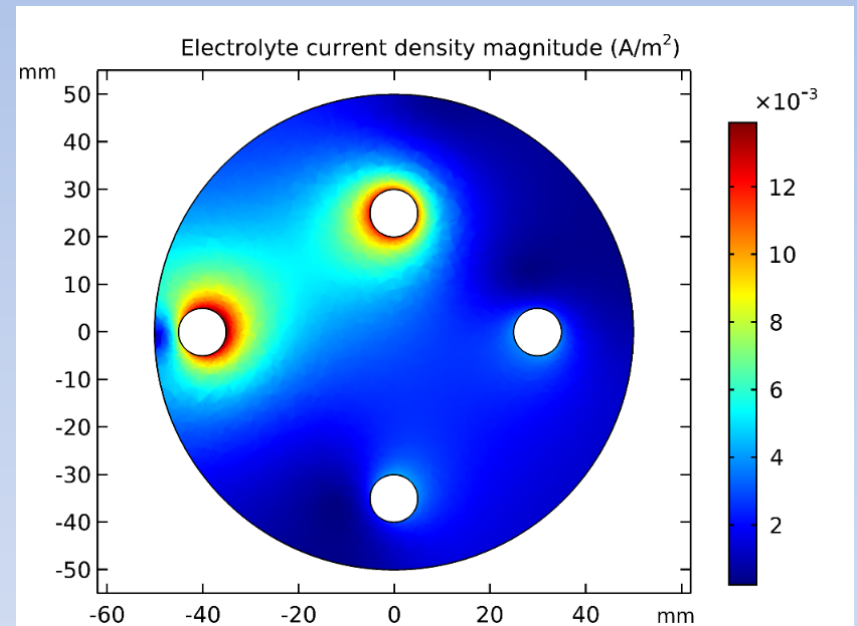
plane at $z = 50$ mm



The mechanism is highlighted by plotting the electrolyte potential and the current density in a horizontal plane.

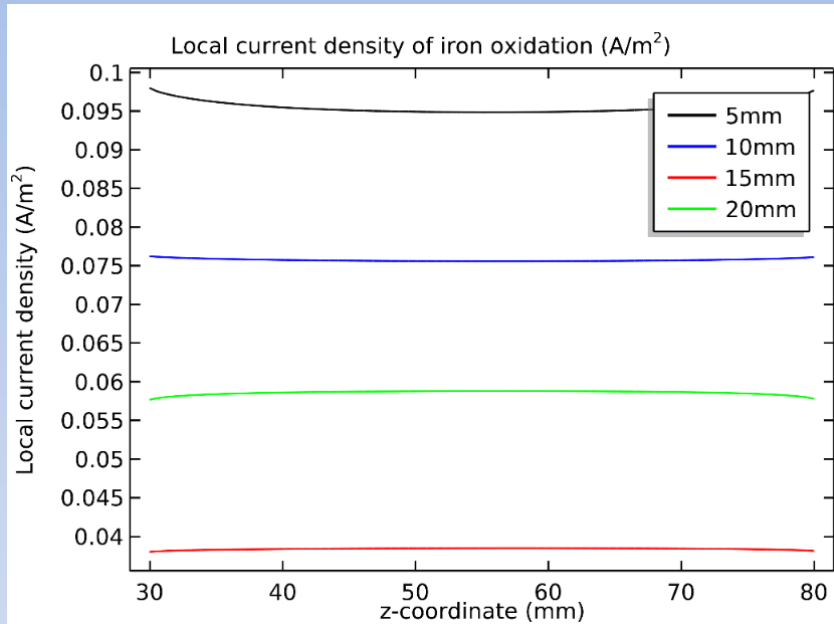
We observe that the areas with the highest potential are located near the outermost oxidized bars.

plane at $z = 50$ mm



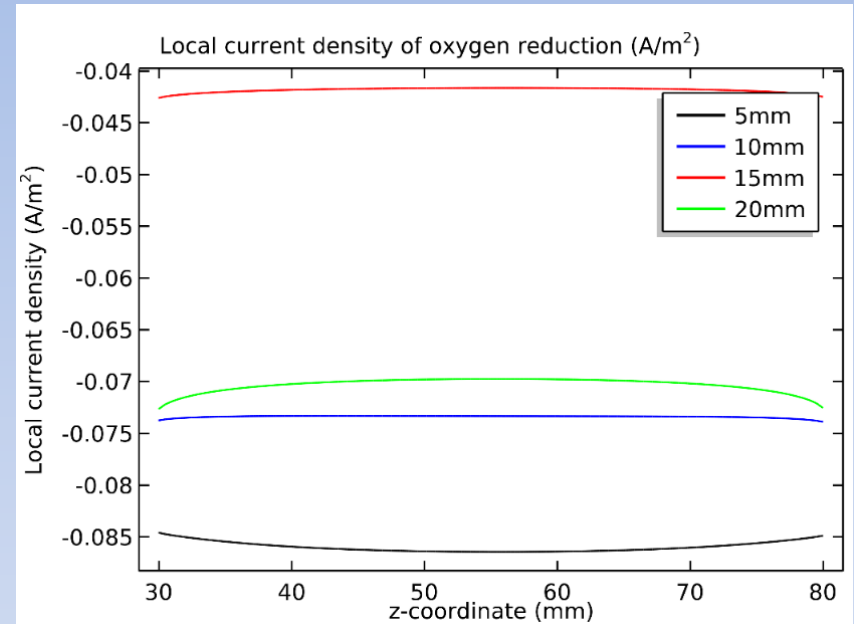
Magnitude of the current density in the electrolyte, on a horizontal surface

Numerical results



The graph plots the oxidation (or corrosion) current density of Fe, computed along a vertical edge opposite the center of the concrete specimen and facing outwards.

The Fe oxidation current for the rod 5 mm from the outer surface is greater than those of the rest, since it is located inside a carbonated area.



The figure provides the computational results of the O_2 reduction corresponding to the same edge.

It shows a similar behaviour for the O_2 reduction, i.e. the reduction current density is greater for the outermost reinforcement, where the O_2 also diffuses more rapidly from the environment.

Conclusions

- Using Comsol Multiphysics® 6.1, we have developed a model of reinforcement bars corrosion by incorporating experimental kinetics data to reflect a carbonation mechanism interesting the concrete.
- Starting from experimental values of corrosion potential, corrosion current density, anodic, and cathodic slopes of the Tafel curve, the values of exchange currents have been computed and then used to simulate the corrosion of four reinforcing bars.
- The analysis of the computational results has shown that when the carbonation is more intense, as occurs with the outermost bars, the corrosion potential is more negative, and the current density presents larger values.
- According to these results, the external bars are characterized by stronger corrosion and reduction currents, phenomena depending also on the oxygen concentration values associated to the gas diffusion, process which has been coupled to the corrosion mechanism.

Some references

K. Tuutti, “Corrosion of steel in concrete”, Swedish Cement and Concrete Institute RIT-Stockholm, 1982.

V.G. Papadakis, C.G Vayenas and M.N. Fardis, “Physical and chemical characteristics affecting the durability of concrete”, ACI Materials Journal, 88, N.2, 186-196, 1991.

Z.P. Bazant, “Physical model for steel corrosion in concrete sea structures”, Journal of the structural division-Proceedings of the ASCE, 105, n. ST6, 1137-1153, June 1979.

C. Cao, “3D simulation of localized steel corrosion in chloride contaminated reinforced concrete”, Construction and Building Materials, 72, 434-443, 2014.

D.A. Jones, “Principles and prevention of corrosion”, 2nd Ed., Macmillian Publishing Company, New York, 1992.

Comsol AB, Corrosion Module, User’s Guide, Version 6.1, 2022.

Comsol AB, Chemical Reaction Engineering Module, User’s Guide, Version 6.1, 2022.

Acknowledgements

Many thanks for your attention !

We would like to also acknowledge: