Durable and Environmental design of Monitored COncrete structures in Marine environment

Stéphanie BONNET Professeure d'université
Nantes Université Laboratoire GeM UMR 6183

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https://orcid.org/0000-0003-0027-344X
https://cv.archives-ouvertes.fr/bonnet-s/

Francois BIGNONNET: Maître de Conférences
Harifidy RANAIVOMANANA: Maître de Conférences
Abdelhafid KHELIDJ: Professeure des Université
Franck SCHOEFS: Professeur d' Universités
Romain CLERC: Maitre de Conférences

Jack ATALLAH
Marie-ang EID
Khodor EL ACHRAFI
Gayelle FAHED
Mohamad ALI AHMAD



Outline

0 **Préambule: présentation du laboratoire et des formations GC de Nantes université**

1 **Introduction**

Contexte de l'étude
Genèse du Projet
Objectifs et programme de recherche

2 **Task 2: Monitoring with ERT for input data of chloride transport modelling**

3 **Task 3: Homogenization techniques to get transport properties**

4 **Conlusions**



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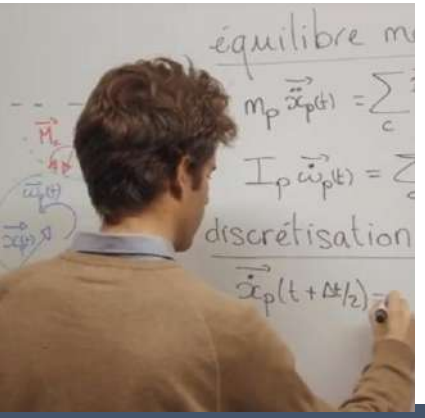
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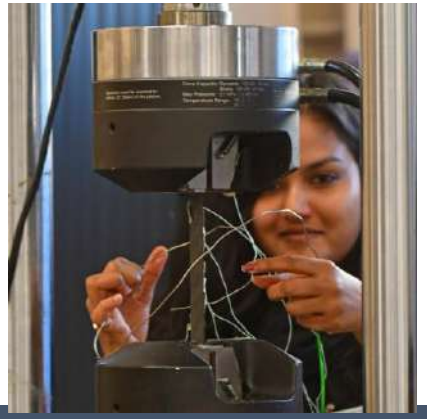
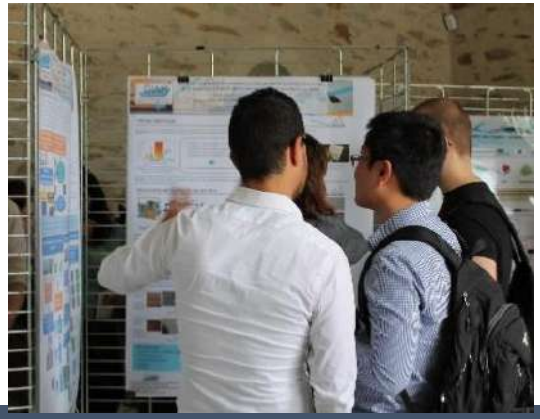
4 Conclusions

GeM: Institut de Recherche en Génie Civil et Mécanique

UMR 6183 – Nantes Université – Centrale Nantes - CNRS





Le GeM

Unité Mixte de Recherche de Nantes Université, Centrale Nantes et du CNRS since 2004.

> Experimental theoretical and numerical skills in the fiels of Mecanics and civil engineering

GeM: Institut de Recherche en Génie Civil et Mécanique

UMR 6183 – Nantes Université – Centrale Nantes - CNRS



80 researchers or teacher/researchers
40 technical and administrative staff
More than **110** PhD and post doc or research engineers

GeM: Institut de Recherche en Génie Civil et Mécanique

UMR 6183 – Nantes Université – Centrale Nantes - CNRS

2 cities 4 places and 3 establishments

Nantes Université

1 IUT Saint-Nazaire

2 Polytech Nantes

3 Faculté Sciences et Techniques

CENTRALE NANTES

4 Centrale Nantes

cnrs

4 CNRS
Site de Centrale Nantes





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9 thematic research units

Environnemental Géoméchanics	Numerical modelling	Structural dynamic and earthquakes
Green engineering approaches	Mecanics and Multi-scales physics of materials	Process and durability of structures
Bio mecanics	Measurements data, sensor and monitoring	Rapid Manufacturing Processes



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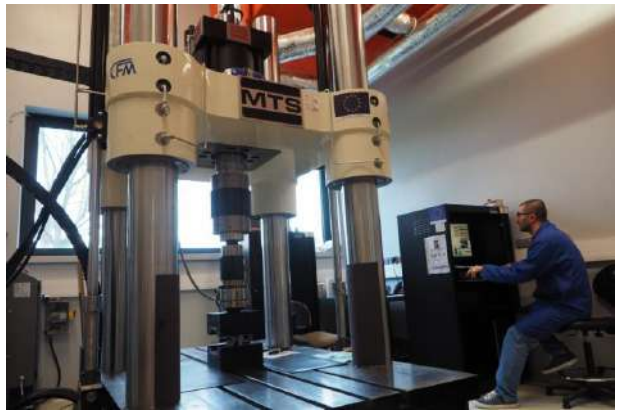


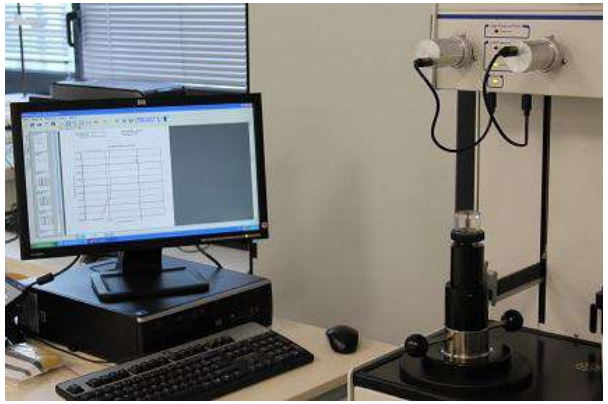
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Experimental plateform connected to research unit INGVERte & DURPRO

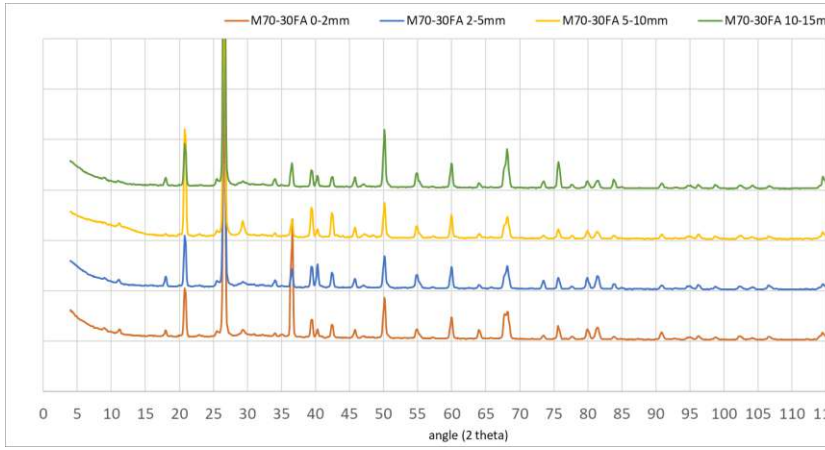
Mechanics and Microstructure







ThermoGravimetry

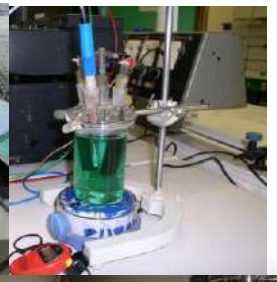


XRD

Durability



















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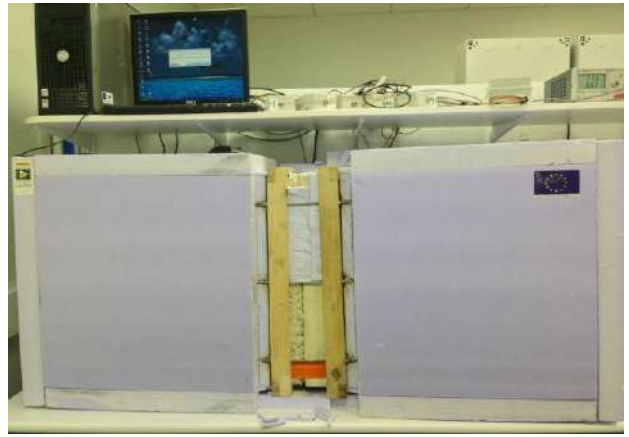
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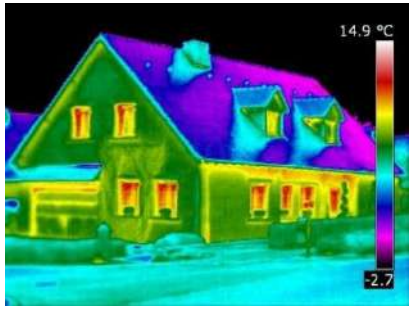
Different scale and materials



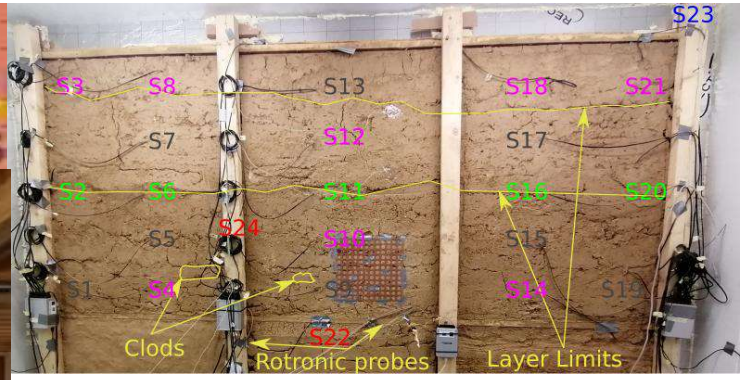




Specimen to real scales
Experimental versus numerical







Thèse Junior TCHIOTSOP *(2019-2022):*

Tchiotsop et al. CBM 2022

Tchiotsop et al. Heat and Mass Transfer2023



Plan de l'exposé

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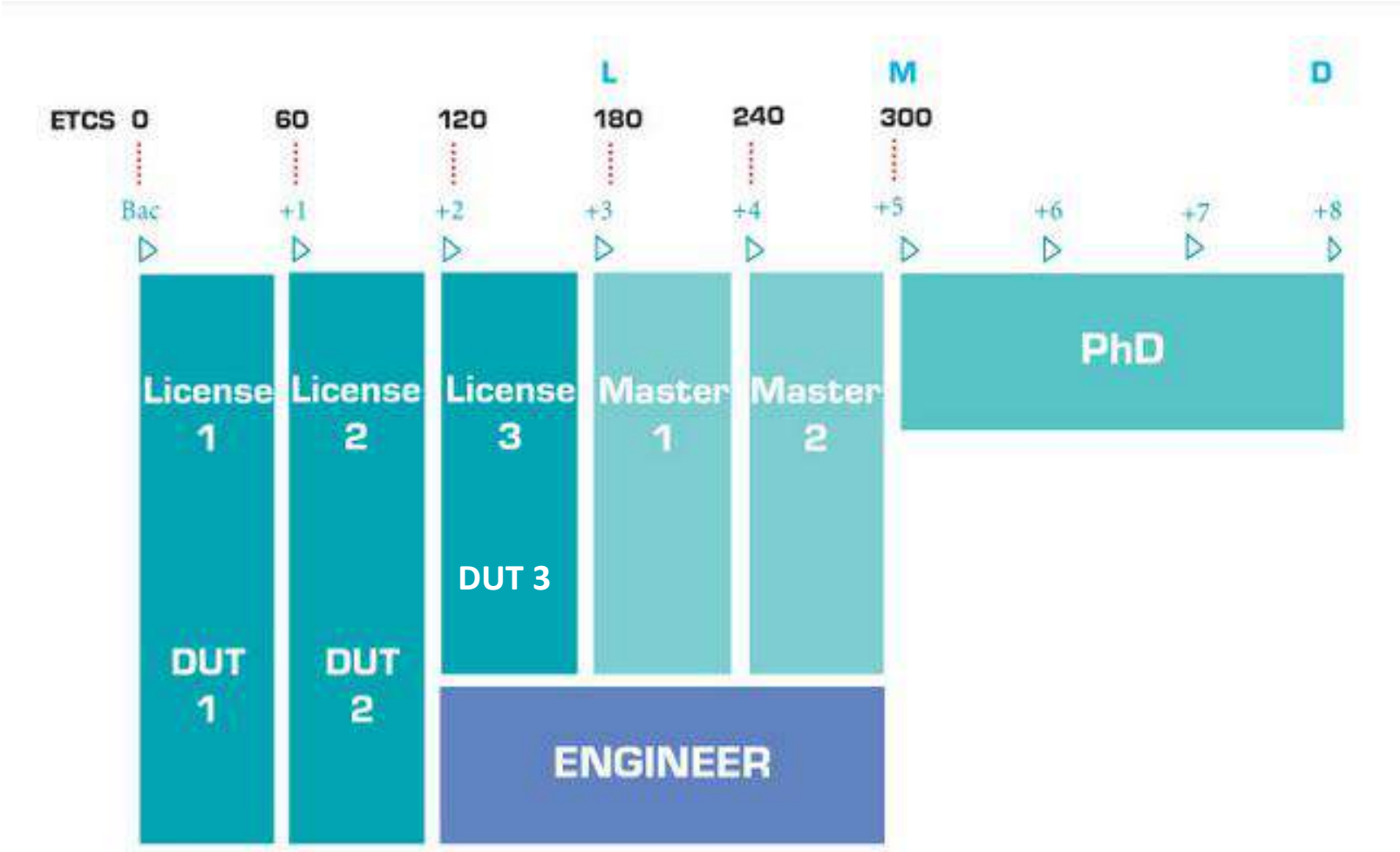
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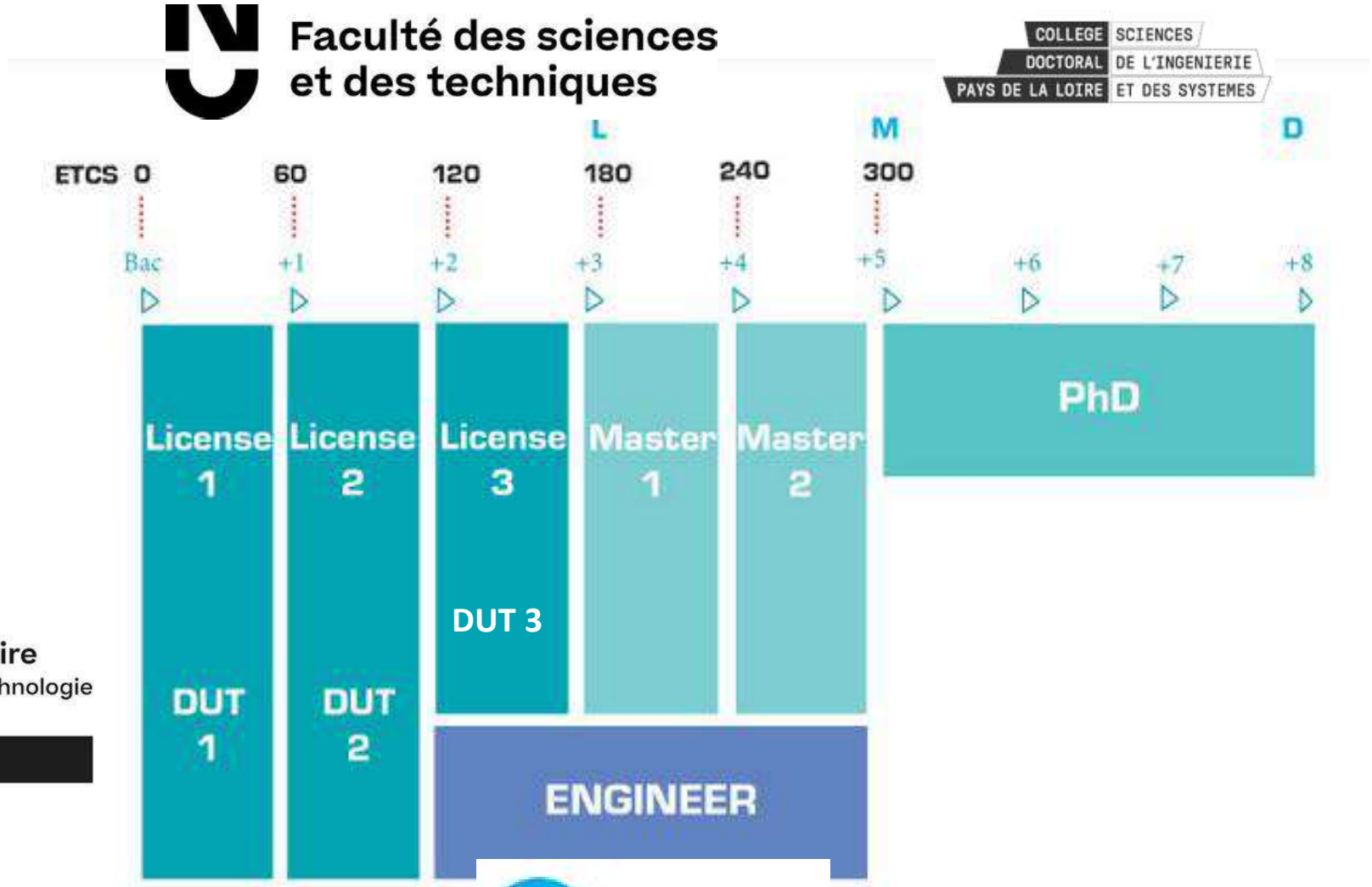
Education in NU: Civil engineering LMD system (Bachelor's–Master's–PhD)

French Education: civil engineering at NU



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IUT Saint-Nazaire
Pôle Sciences et technologie

Nantes Université

Education in NU: Civil engineering LMD system (Bachelor's–Master's–PhD)

Bachelor in Civil engineering: bac+3

IUT Saint-Nazaire
Pôle Sciences et technologie
Nantes Université

CE departement

Five specializations: buildings, roads, buiding retrofitting,

Master and engineer: bac +5

Faculté des sciences et des techniques

LMGC
Licence Master Génie Civil
U.F.R. SCIENCES ET TECHNIQUES
NANTES UNIVERSITE

3 specializations: Buidings conception and realisation, Pubic and Marine Works

POLYTECH NANTES

Département GC

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0 Préambule: présentation du laboratoire

1 **Introduction**

problematic
Project genesis
Objectives and research program

2 Task 2: Monitoring with ERT for input data of chloride transport modelling

3 Task 3: Homogenization techniques to get transport properties

4 Task 4: Multi-criteria optimization and recommendations

Problematic: new structures







The length of the coastline of Metropolitan France is around **3427 km** (Wikipedia.org)

New RC structure

- It has to maintain its mechanical properties throughout its life (Eurocode 2)
- It has not to be deteriorated by aggressive environment : transport and physical properties of concrete related to its durability

Should be maintained during the predefined service life of RC structures in aggressive environment.



PROJECT CONREPNET 2007:

Corrosion of steel reinforcement

➔ Main cause of deterioration (54%)

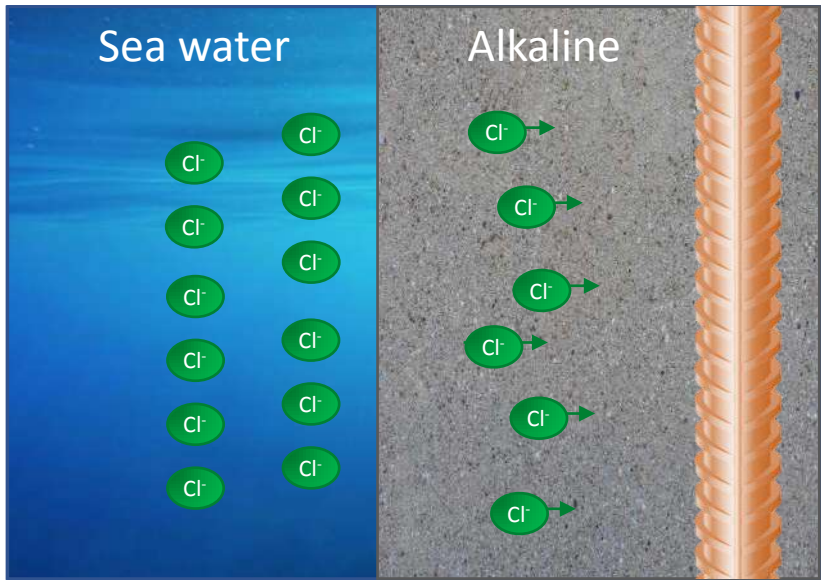
Reparation: defeat for 50% of cases *Project*

Poblematic: durability

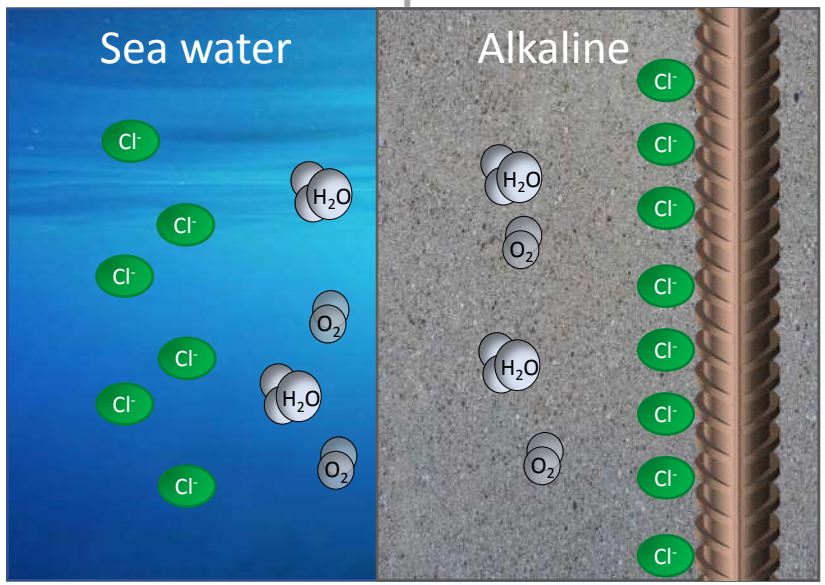




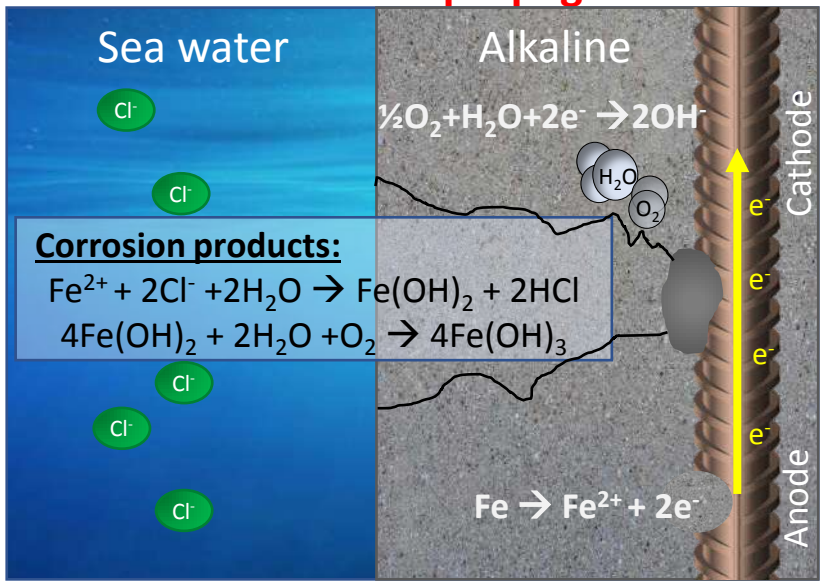
1- Corrosion initiation

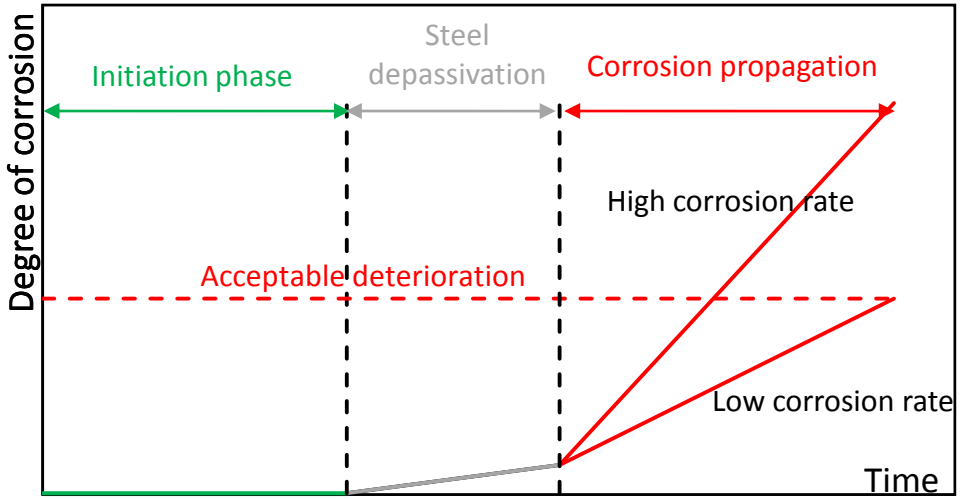


2- Steel depassivation



3- Corrosion propagation





Critical chloride concentration at the steel surface

pH of the cementitious matrix depending on the:
- $Ca(OH)_2$ content

Cementitious formulation, cure and activation → Hydration mechanism

- Ionic conductivity
- Pore solution chemistry
- Moisture content
- Dissolved oxygen

Porous structure → Transport Properties → Corrosion initiation

Chloride critical value → Steel depassivation

Interstitial solution

Alkalinity → Material conductivity → Corrosion propagation

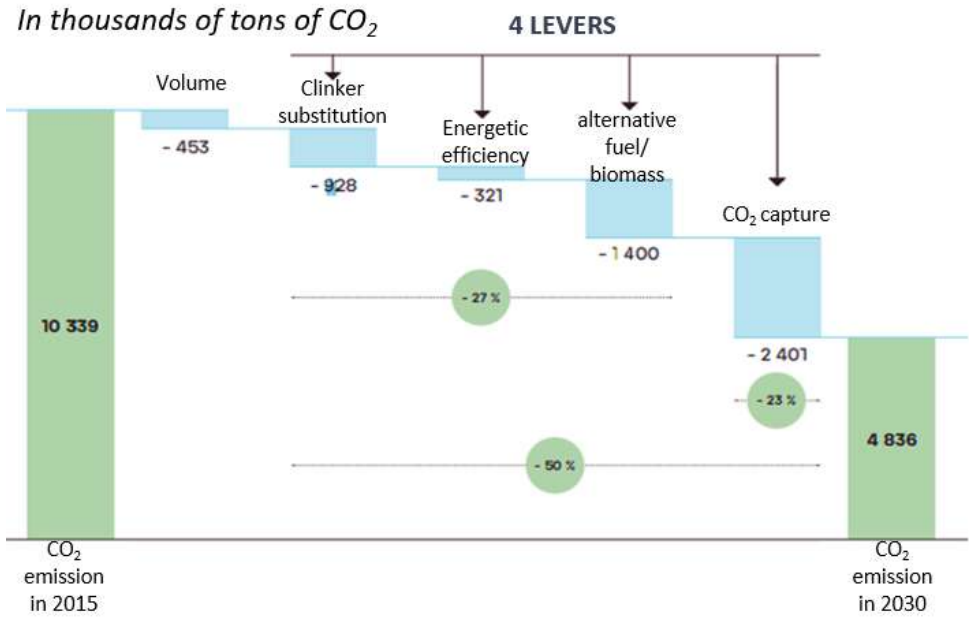
Poblematic: reduction of CO_2



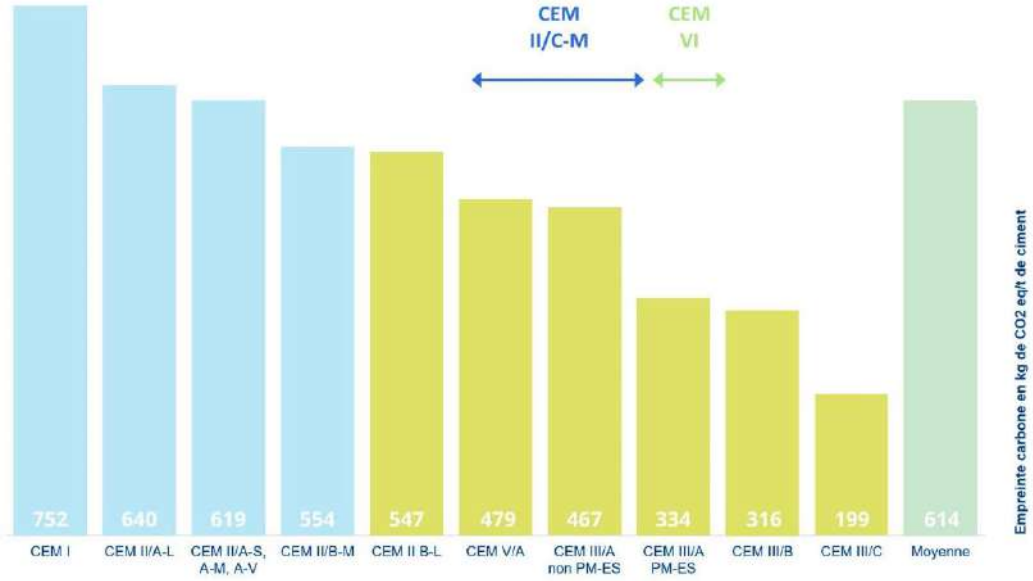


The French Cement Industry Union unveiled a new roadmap to address major challenges in decarbonisation and industrial sovereignty

Reduction of CO_2 emission between 2015 and 2030



Cements with a low carbon footprint, "low clinker content", were standardized in May 2021, which involve clinker combined with one or more components: CEM II/C-M and CEM VI



Reference: "Moyenne France Ciment" for French cements, in compliance with the standard NF EN 15904+A2 and its national supplement NF EN 15804+A2/CN.

Introduction: project genesis





GeM + UGE : Anne VENTURA

Van Loc TA PhD (2014 2017)

LCA and durability modelling

Carbonation process

Construction and Building Materials 125 (2016) 172–181

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A new meta-model to calculate carbonation front depth within concrete structures

Van-Loc Ta [a,*], Stéphanie Bonnet [b], Tristan Senga Kiesse [a,c], Anne Ventura [a]

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Application of sensitivity analysis in the life cycle design for the durability of reinforced concrete structures in the case of XC4 exposure class

T.A. Van-Loc [a], Tristan Senga Kiesse [b], Stéphanie Bonnet [c,*], Anne Ventura [a,d]

[a] LUNAM Université, Université de Nantes, GeM, Institut de Recherche en Génie Civil et Mécanique – CNRS UMR 6183 – Chaire Génie Civil Eco-construction, France
[b] UMR SAS, INRA, Agrocampus Ouest, 35000 Rennes, France
[c] LUNAM Université, Université de Nantes, GeM, Institut de Recherche en Génie Civil et Mécanique – CNRS UMR 6183, France
[d] LUNAM Université, des Sciences et Techniques, Institut Français Transports Aménagement Réseaux (IFSTTAR – MAST – GPEM), 44340 Bouguenais, France

DOI: 10.

Check for updates

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

RESEARCH AND ANALYSIS

Design of concrete

Setting a new basis for improving both durability and environmental performance

Anne Ventura[1,2] | Van-Loc Ta[1] | Tristan Senga Kiessé[1,3] | Stéphanie Bonnet[4]

Introduction: project genesis





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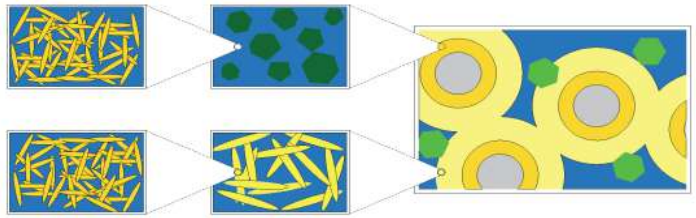
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LCA & Durability: identical input data

Material mixture → **Concrete properties**



Homogeneization technics: GeM
(Thèse M Achour 2015 - 2018)

GeM

Introduction: project genesis





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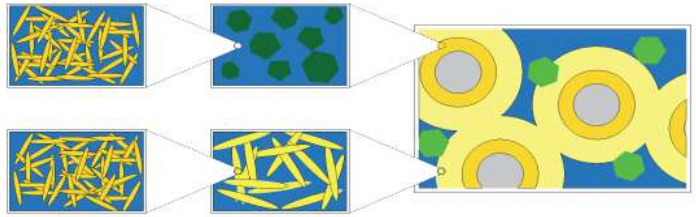
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Homogeneization technics: GeM
(Thèse M Achour 2015 - 2018)

GeM + UGE: Géraldine VILLAIN

Project CA2M-COM 2018

Critical Analysis for Monitoring and Modelling chloride penetration in COncrete structures in Marine environment

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Electrical resistivity tomography results analyzed with two inversion methods to determine chloride profiles on BFS concrete having very high electrical resistivity

Mohamad Khodor EL Achrafi [a,b], Stéphanie Bonnet [a,*], Géraldine Villain [b]

Introduction: research program





Minimizing the environemental impacts and the cost of marine reinforced structures monitored by embedded sensors

DEMCOM
Service life : period of penetration of chloride into the concrete cover depth

Task 1
Start, Follow-up and Coordination

Task 3
Homogenization for Life Cycle Performance (LCP)

Task 2
Monitoring to get input data for LCP

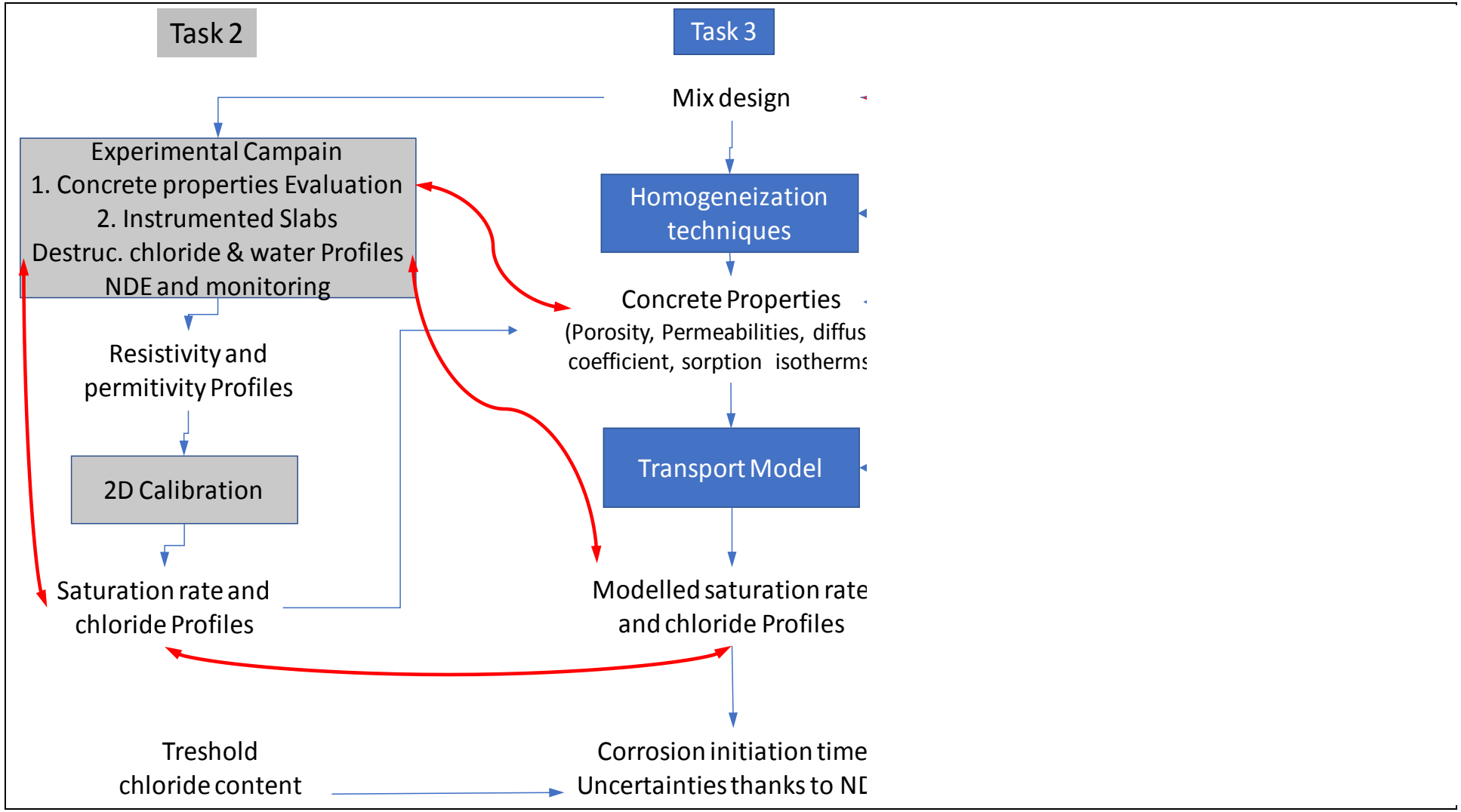
Task 4
Multi-criteria optimization
Life Cycle Cost Analysis (LCC)
Life Cycle Assessment (LCA)

Introduction: schéma conceptuel





S. Palma Lopes & F. Ranaivomanana **F. Bignonnet / A. Ventura**

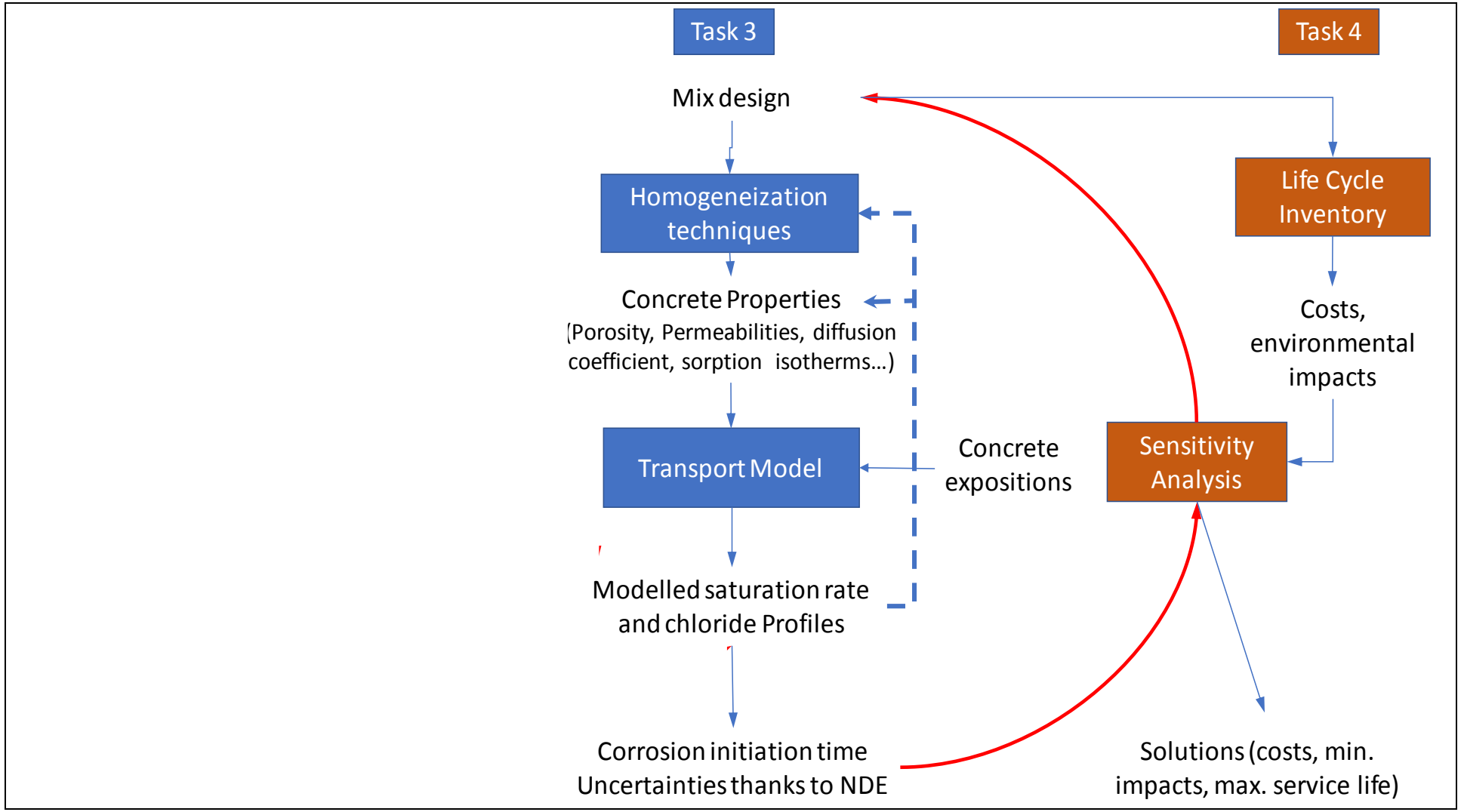


Introduction: schéma conceptuel





F. Bignonnet / A. Ventura **A. Ventura & C. Crémona**

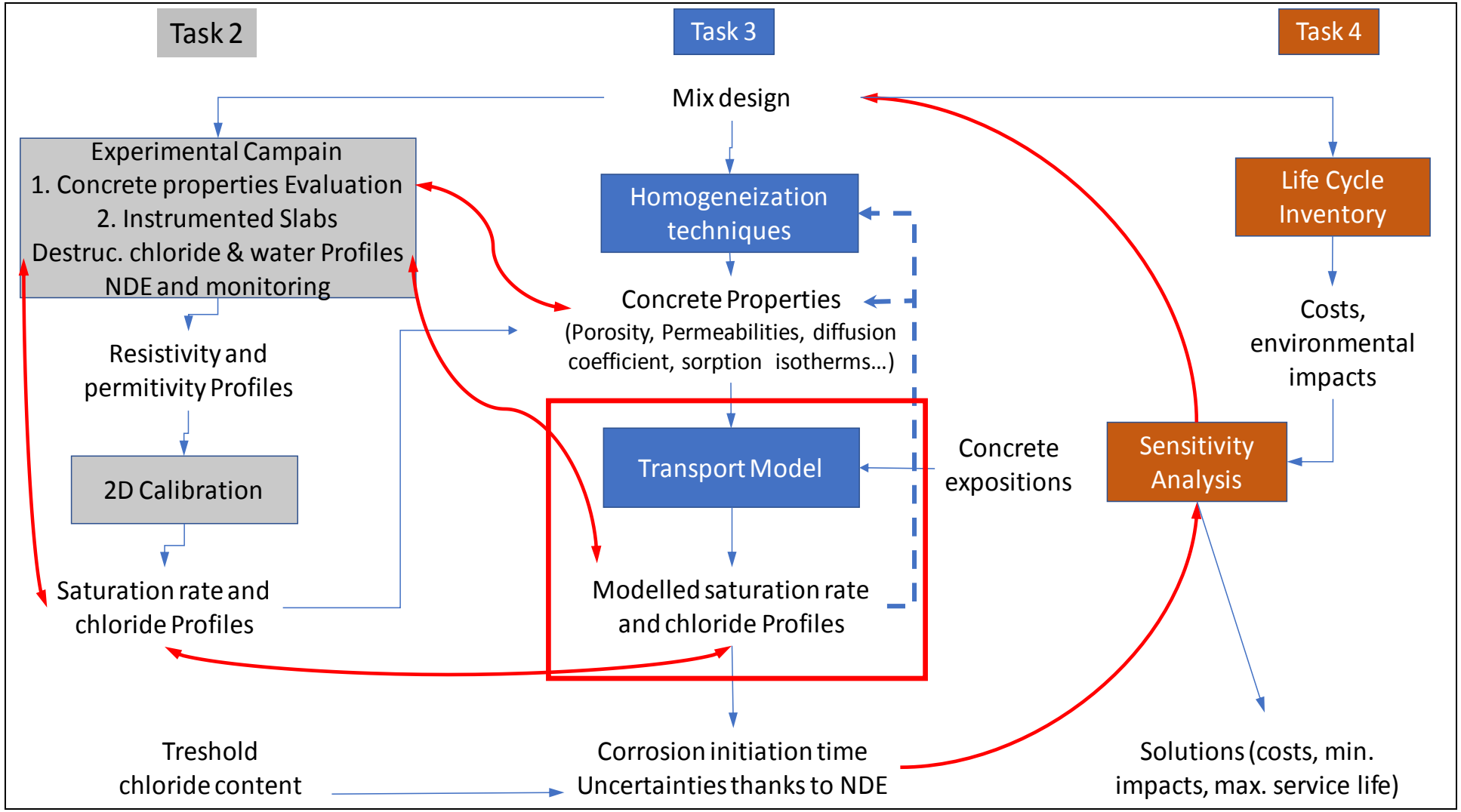


Introduction: schéma conceptuel





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Task 2: Monitoring de propriétés électriques du béton par capteurs noyés





PhD M.A. EID / UG.Eiffel / NU (GeM)

Objectifs

Resistivity and chargeability profiles by embedded sensors

↓

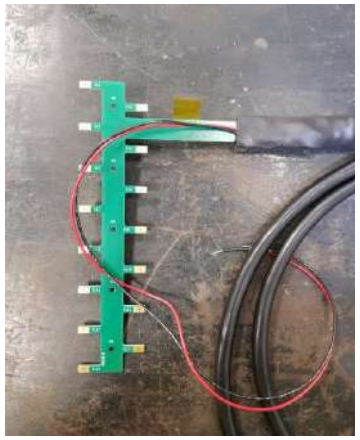
Chloride and water content profiles into concrete

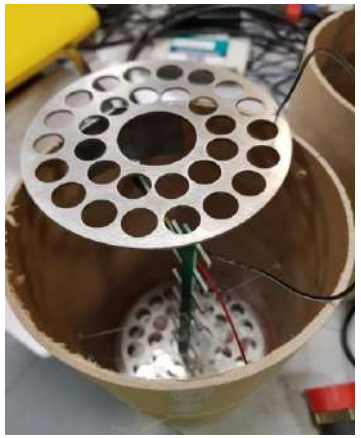
↓

Inversion model to get the input date of the durability modeling

↓

Chloride profiles simulation/ comparison with experimental data





UGE: Resistivity scale measurement
Thèse de J. Badr

Task 2: Monitoring de propriétés électriques du béton par capteurs noyés





ElAchrafi, CBM, 2023

PhD M.A. EID / UG.Eiffel / NU (GeM)

Objectifs

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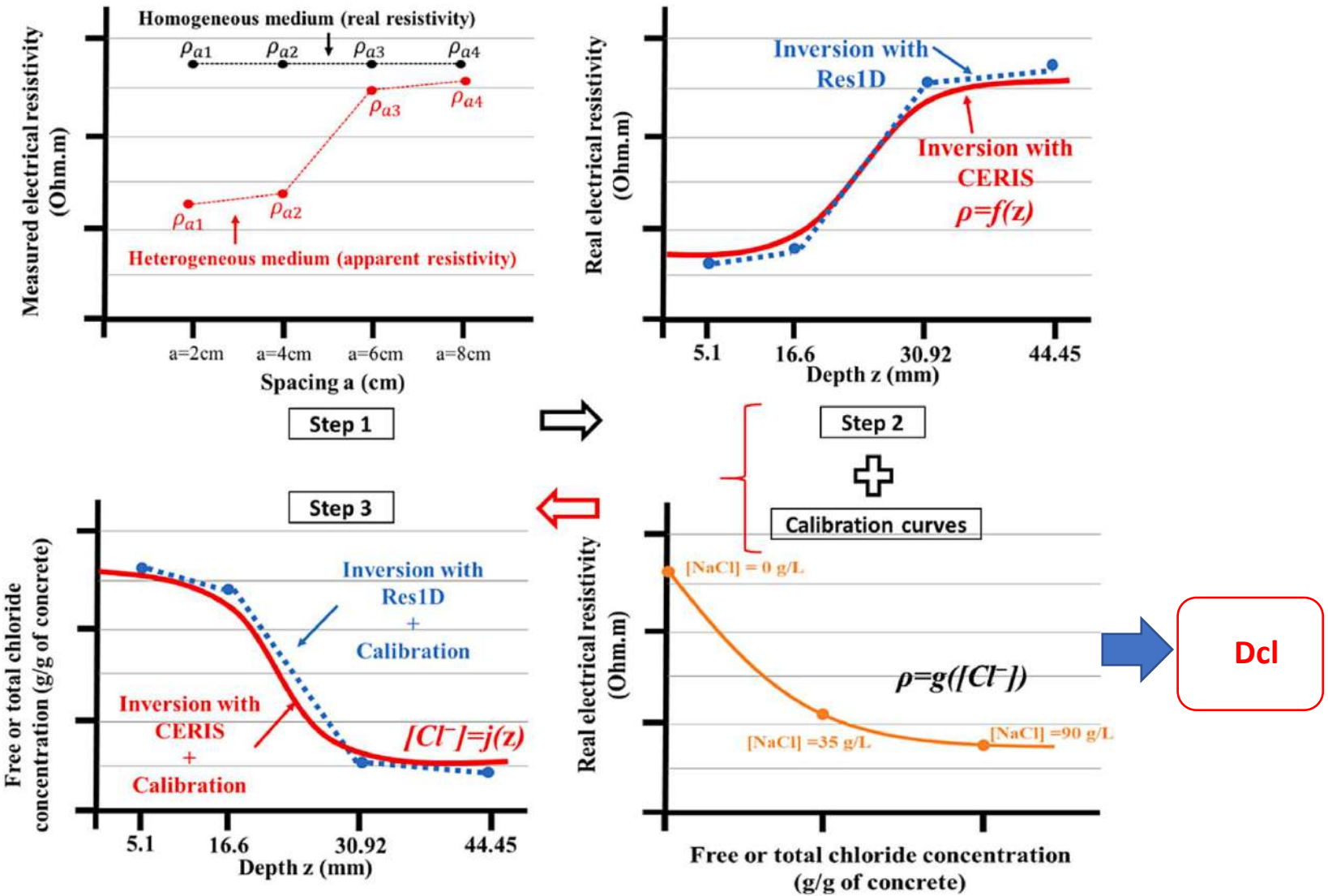
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Chloride profiles simulation/ comparison with experimental data



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PhD M.A. EID / UG.Eiffel / NU (GeM)

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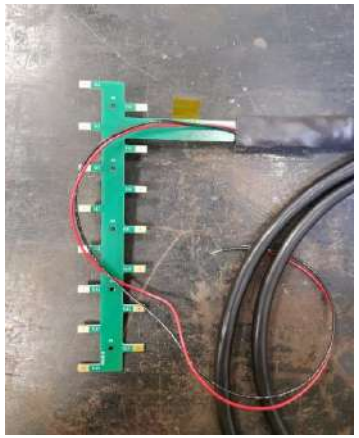
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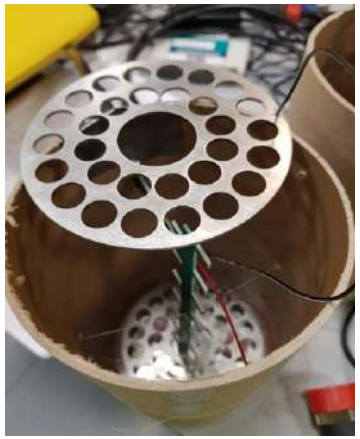
Chloride profiles simulation/ comparison with experimental data

Expérimental program

Scale of specimen

- ✓ Monitoring of hydration during period
- ✓ Diffusion + imbibition
- ✓ Calibration procedure





UGE: Resistivity scale measurement
Thèse de J. Badr

Scale of slab

- ✓ Monitoring of slab during the tidal exposture for 3 years



GeM/NU
2 tanks (LxlxH)
4x1x2m3)

Task 2: Monitoring de propriétés électriques du béton par capteurs noyés





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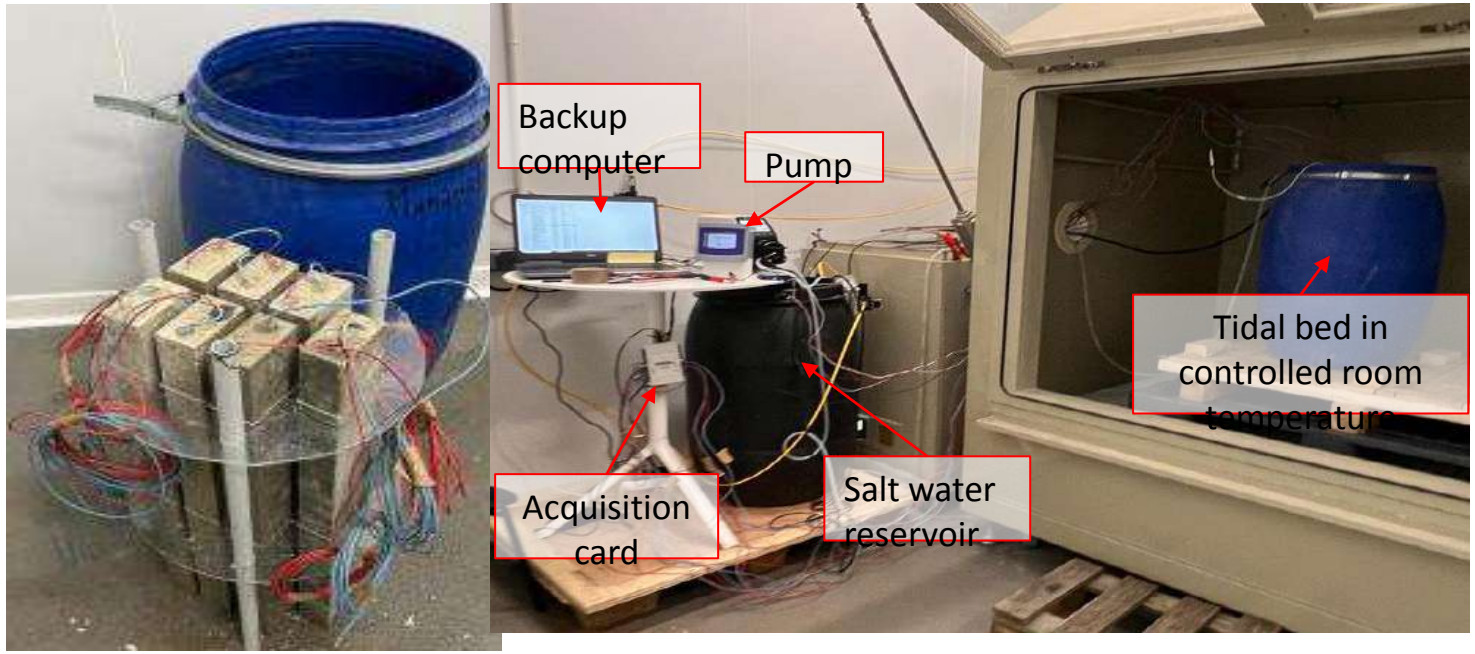
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Inversion model to get the input date of the durability modeling

↓

Chloride profiles simulation/ comparison with experimental data

Expérimental program on different kinds of cementitious beams



Plan de l'exposé





0 Préambule: présentation du laboratoire

1 Introduction

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2 Task 2: Monitoring with ERT for input data of chloride transport modelling

3 Task 3: Homogenization techniques to get transport properties

4 Conclusions

Task 3: general methodology





Input data for LCA LCC & durability modelling

formulation du béton

type de ciment
taux de substitutions minérales
rapport eau / liant
nature des sables et granulats

paramètres indépendants de la composition du béton

- coefficients de diffusion dans les pores capillaires et gels CSH
- paramètres morphologiques (géométrie microstructure)
- paramètres d'hydratation

modèle multi-échelles
modèle d'hydratation

propriétés du béton

porosité
coefficients de diffusion
composition solution porale
isotherme de fixation
résistivité électrique
facteur de résistance
perméabilité intrinsèque et relative
courbe de pression capillaire

conditions d'exposition

saturation en eau initiale (5)
température
salinité et humidité extérieures
scénario d'exposition :
- totalement saturé
- imbibition ou séchage
- cycles de marnage

modèle macroscopique de transport ionique et hydrique

In tidal area

évolution temporelle et spatiale :

- saturation en eau
- pressions gaz et liquide
- concentrations ioniques
- concentration Cl- fixés

Task 3: general methodology





Input data for LCA LCC & durability modelling

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Block 1: multi-scale modelling

Block 2: model in non saturated concrete & SA

Task 3: Chloride transport into concrete structures in tidal conditions





- Hygric / Cl transport model – **Sensitivity Analysis (Morris) on t_{crit}**:

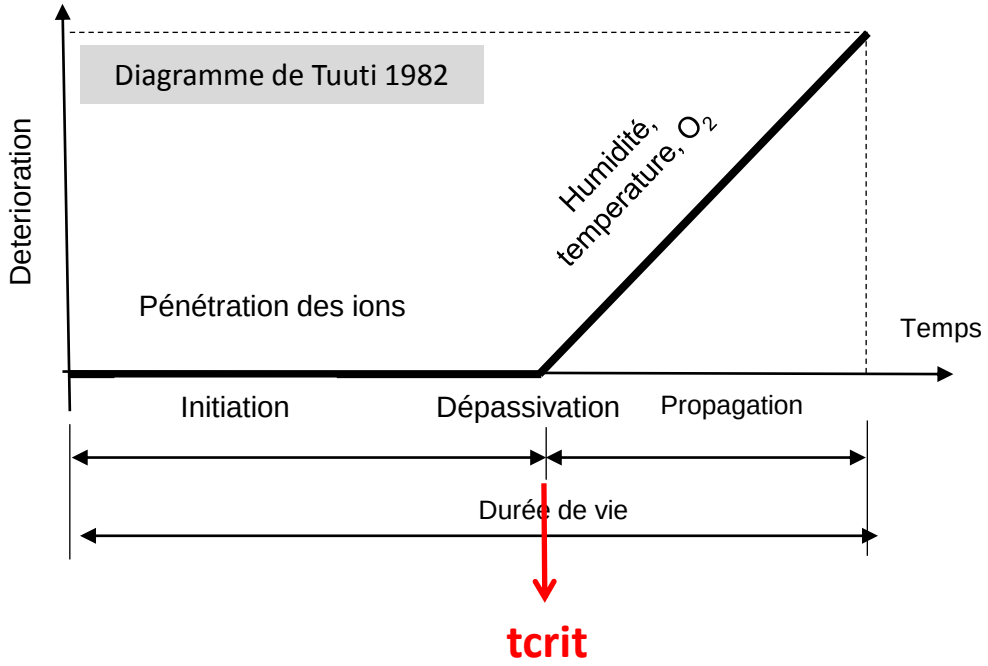
Post Doc N. REUGE / NU (GeM): Reuge & al Applied Ocean research

$$\begin{cases} \frac{\partial}{\partial t}(\varphi S_l) - \frac{\partial}{\partial x}\left[K k_{r,l}\frac{\partial P_l}{\partial x}\right] = 0 \\ \frac{\partial}{\partial t}\left(\varphi S_l c_{Cl,f} + C_{Cl,b}\right) - \frac{\partial}{\partial x}\left[D_{eff}\frac{\partial c_{Cl,f}}{\partial x} + c_{Cl,f}\frac{K k_{r,l}}{\eta_l}\frac{\partial P_l}{\partial x}\right] = 0 \end{cases}$$

with:

$$\begin{cases} S_l(Hr) = \left[1 + \left(-\frac{\rho_l RT}{M_w}\cdot\frac{1}{a}\ln(Hr)\right)^{\frac{1}{1-m}}\right]^{-m} \\ k_{r,l} = S_l^{\frac{1}{2}}\left[1 - \left(1 - S_l^{1/m}\right)^m\right]^2 \\ D_{eff} = D_{eff,0} S_l^{\lambda} \\ C_{Cl,b} = \mu\left(S_l^{\beta} c_{Cl,f}\right)^{\gamma} \\ P_l = P_{atm} - P_c(S_l) = P_{atm} - a\left(S_l^{-1/m} - 1\right)^{1-m} \end{cases}$$

Baroghel Bouny 2011



Input Parameters	S_i^*	S_i^* / S_i	σ_{Si} / S_i^*	
C_{crit}	**1.05**	1	**0.30**	Linear effects
$D_{eff,0}$	**0.99**	-1	**0.06**	
λ	**0.62**	12.4	1.56	Non-linear or interactions with other parameters
m	0.37	1	1.05	
μ	0.26	8.7	1.27	
S_{l0}	0.22	1	1.05	
β	0.15	3	1.60	
K	0.08	2	1.13	
φ	0.08	-2.7	1.00	

Task 3: Homogenization techniques to get transport properties





Focus on slad addition
PhD of Jack Attalah

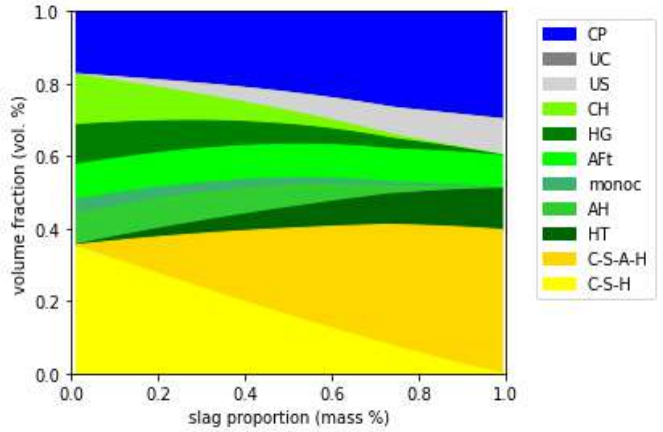


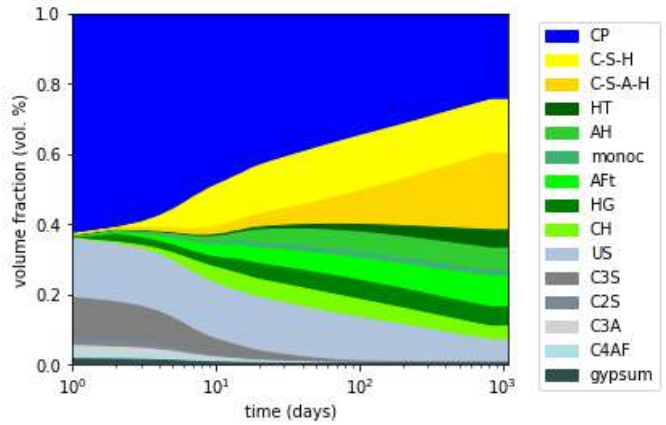
Transport model

Hydratation of cement with slag

Réactifs
Tricalcium silicate C_3S
Dicalcium silicate C_2S
Tricalcium aluminate C_3A
Tetra-calcium aluminoferrite C_4AF
Slag
Water

Produits
Calcium hydroxide CH
Calcium silicate hydrate C-S-H
Calcium aluminate hydrate C-S-A-H
ettringite AFt
Calcium monosulfoaluminate AFm
Calcium carbonate CC
Hydrotalcite HT
Hydrogarnet HG
Tetracalcium AH
monocarbonate monoc
capillary pores CP





Coupling between chemical hydration modeling (Chen & Brouwers Mat Sci 2007) and kinetics modeling of clinker (Parott Brtisch Ceram Proc. 1984) and of slag (Attalah CBM,2024)

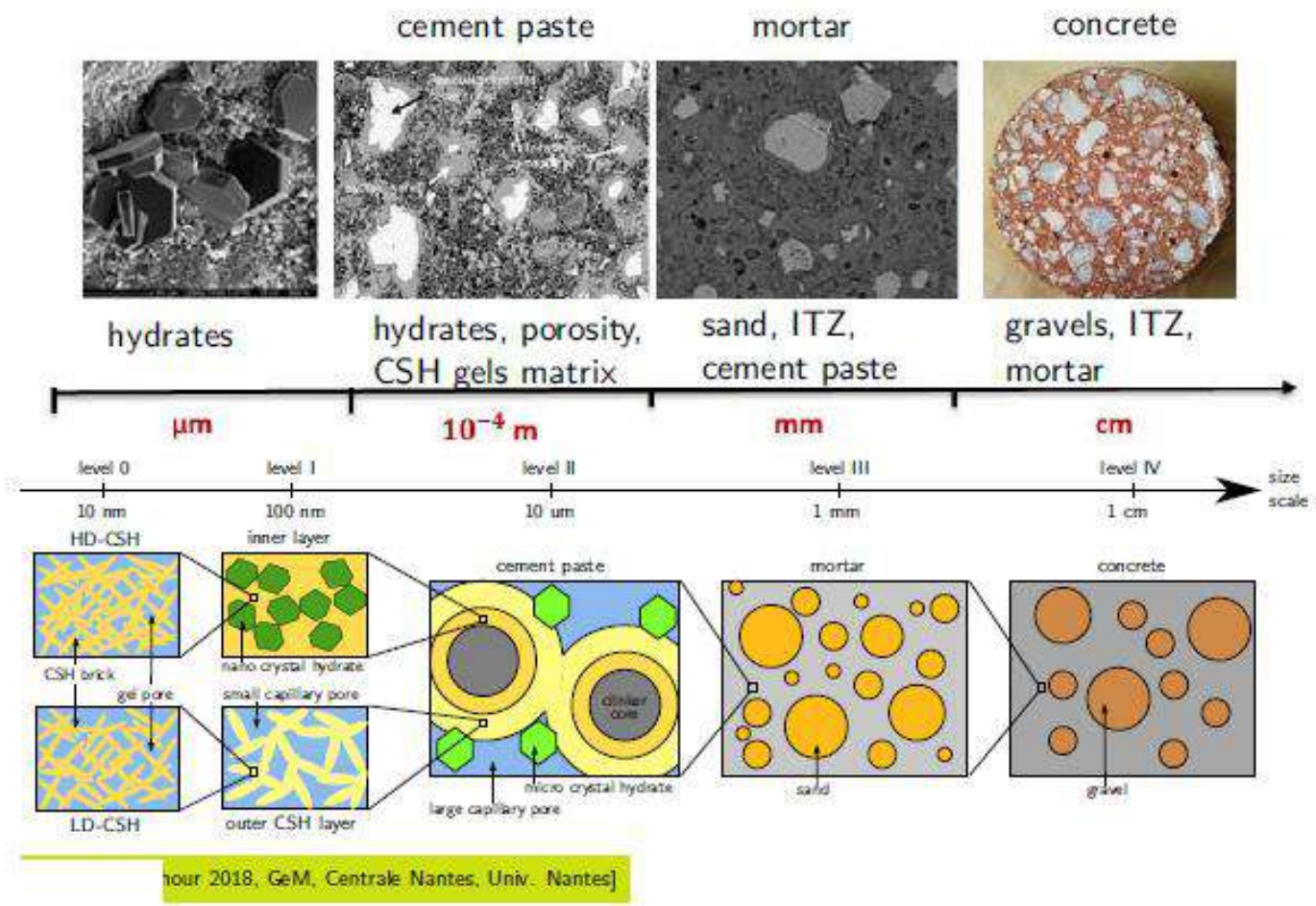
Task 3: Homogenization techniques to get transport properties





Focus on slad addition
PhD of Jack Attalah





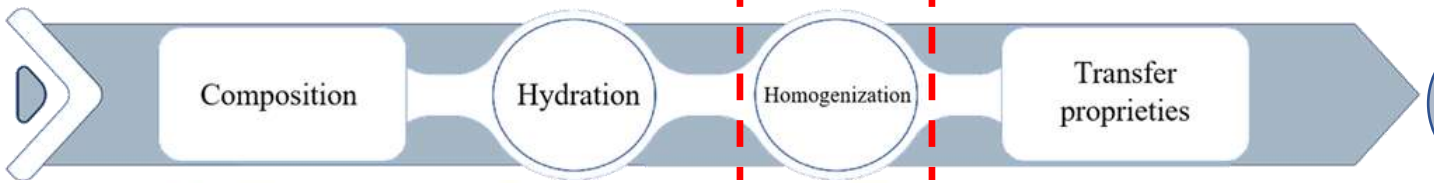
hour 2018, GeM, Centrale Nantes, Univ. Nantes]

Task 3: Homogenization techniques to get transport properties

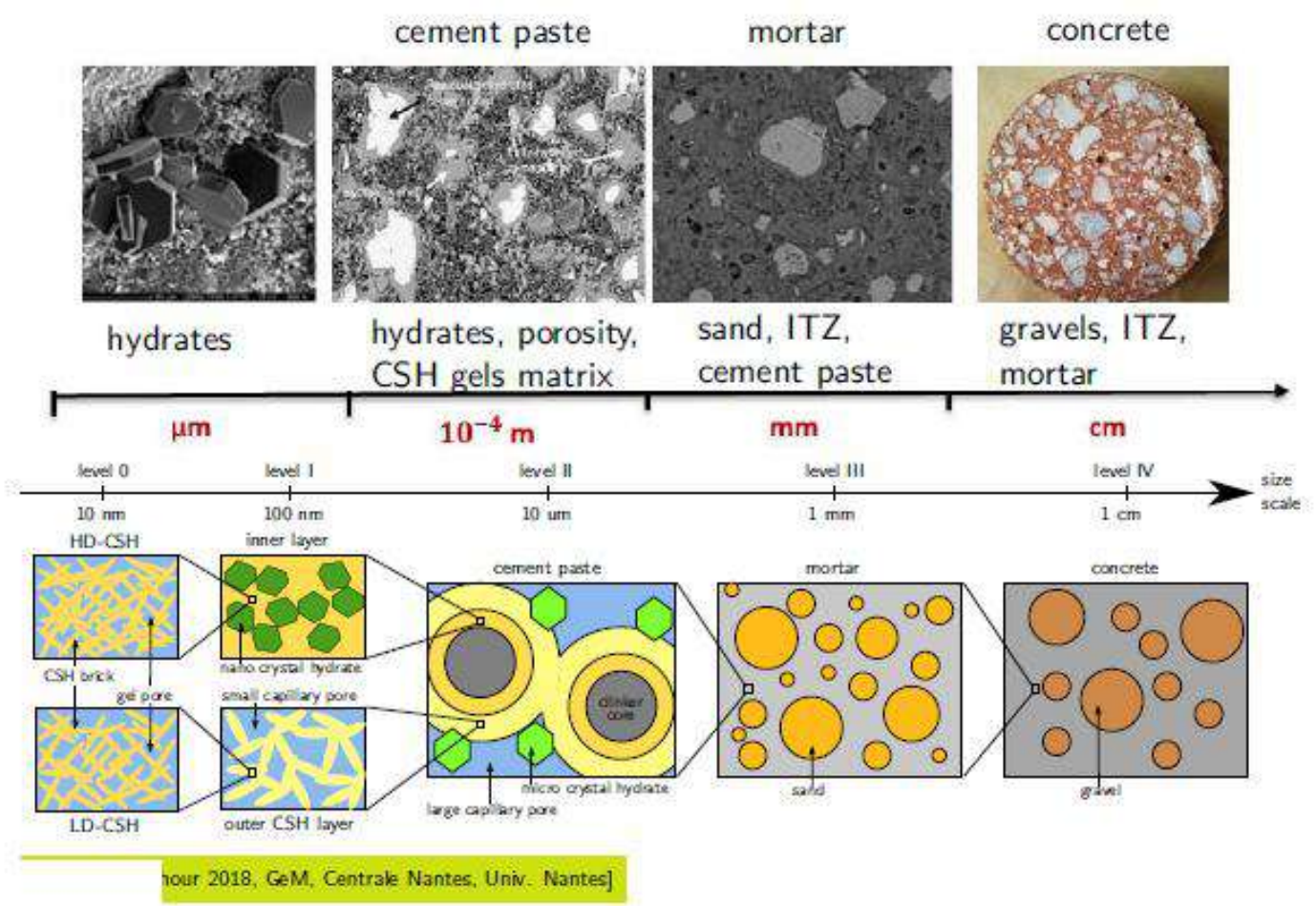




Focus on slad addition
PhD of Jack Attalah

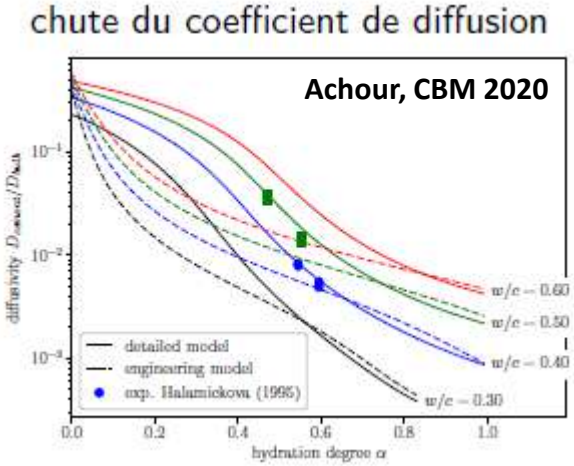


Transport model



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Comparison with experimental measurements done by other PhD students



Work in progress for concrete with slag addition

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Conclusion: multi-criteria optimization recommendations





LCC model

- Identify an appropriate chloride ingress model in order to predict the service life time of the concrete.

LCA model

- Developing an LCA model for different types of European cement.

LCC model

Integration of the user, direct, labor, administrative costs in order to assess the lCC of different concrete formulations.

Integrated model

- Modelling the chloride ingress model with LCA model + sensitivity analysis.
- Modelling LCA with LCC model + sensitivity analysis.
- Coupling the three models together + sensitivity analysis.

Conclusion





- Hollistic approach for a RC structure in marine environment

- difficulty to get the hydration phases for ternary binder

- Application to RC structures in marine environment with a strategic impact (international scale of the project)

- Methodology applied for RC structures of Bouygues enterprise

- Other solutions are studied as concrete with fibres or geopolymers



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