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RESHEALIENCE
Ultra High Durability Concrete

Rethinking coastal defence and Green-**e**nergy **S**ervice infrastructures
through en**H**anc**E**d-dur**A**bi**L**ity high-p**e**rformance **ce**ment-based materials

Predicting the long term performance of structures made with advanced cement based materials in extremely aggressive environments: current state of practice and research needs. The approach of the H2020 project ReSHEALience

CONCRETE!
«it is simply a remarkably good building material»

≅ 10 bln ton/year (≅ 4 bln m^3)

More than twice the toal of all other building materials (e.g. steel ≅ 1.7 bln t/y)

The second largest used material after water

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Durability and Sustainability of concrete structures

Testing the durability of concrete structures !?

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Durability and Sustainability of r/c structures

year cost of CORROSION (direct+indirect):
1 trln USD (3.1% US GDP)

Source www.nace.org

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Durability and Sustainability of r/c structures

CON-REP-NET project, showed that 50% of the repaired concrete structures failed once again, 25% of which in the first 5 years, 75% within 10 years and 95% within 25 years. This is just an example of the **urgent need of a profound rethinking** of the concept and design processes for new and repaired R/C structures in aggressive environments in view of cost-effectiveness demands.

Matthews S. (2007) CONREPNET: Performance-based approach to the remediation of reinforced concrete structures: Achieving durable repaired concrete structures. Journal of Building Appraisal 3(1): 6-20.

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Durability and Sustainability of r/c structures

Mankind has become a «geological force»!

Our collective choices continuously shape the scenario!

Museu do Amanhã – Rio de Janeiro

We need a «scenario based» durability modelling framework!

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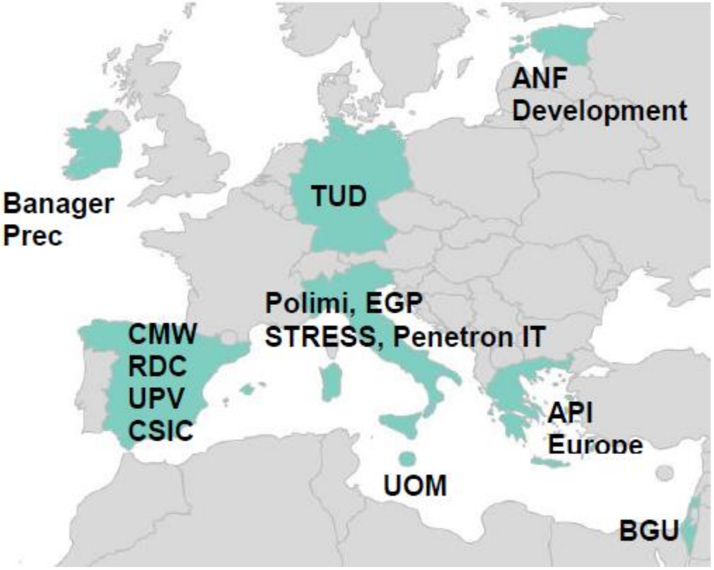
The ReSHEALience project

ReSHEALience (H2020 – GA 760824) – PoliMi coordinator (2018-2021)

www.uhdc.eu

Rethinking coastal defence and green Energy Service infrastructures throuhg ehNhanEd derAbility high-performance fibre reinforced cement based materials



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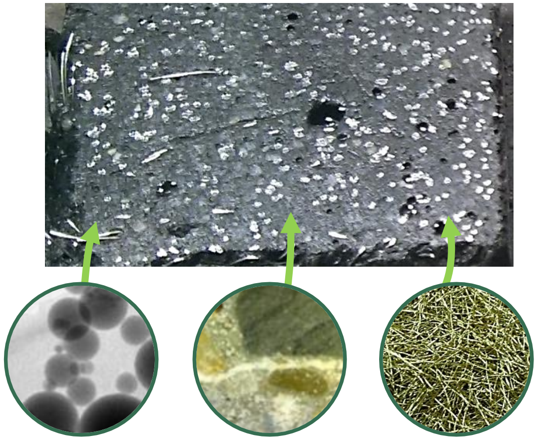
The ReSHEALience project

Ultra High Durable Concrete (UHDC):

"strain-hardening (fibre reinforced) cementitious material with functionalizing micro- and nano-scale constituents (alumina nanofibers, cellulose nanofibers/crystals, crystalline admixtures) especially added to obtain a high durability in the cracked state".

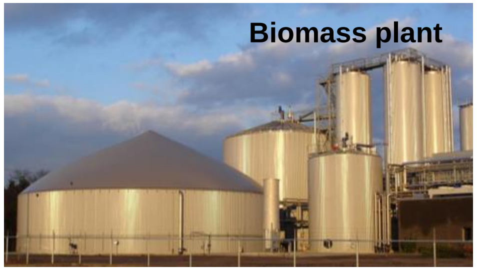
UHPC + functionalities = UHDC



Nanocellulose
densification of matrix and ITZ

Self-healing
sealing of cracks

Nanofibers
crack initiation and growth



A) DURABILITY PROBLEMS IN XS / XA

B) IMPROVED CONCRETE AND DESIGNS

C) INCREASE OF SERVICE LIFE

Liberato Ferrara, Politecnico di Milano

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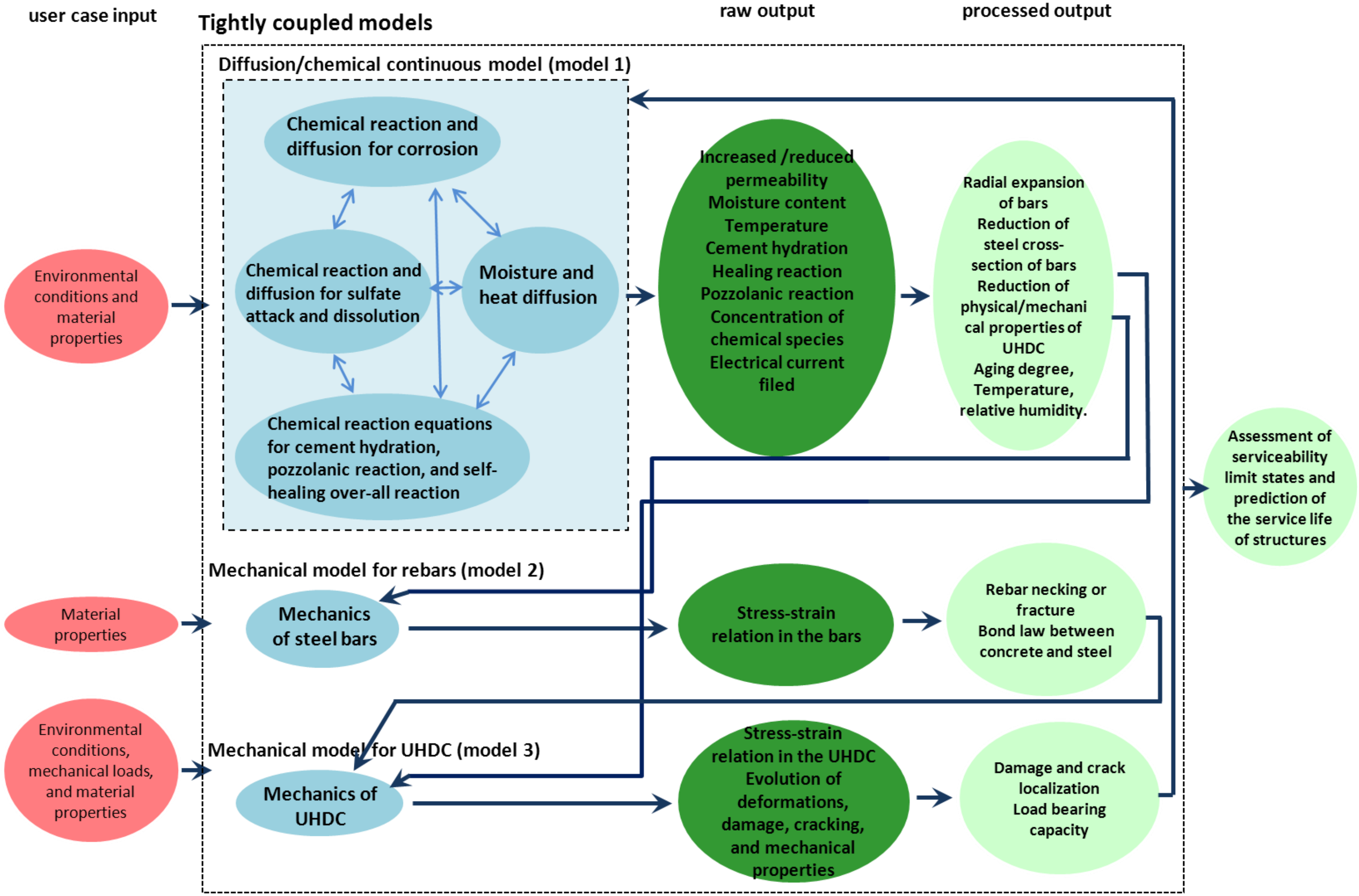
The ReSHEALience project modelling approach



user case input

Tightly coupled models

raw output

processed output

Diffusion/chemical continuous model (model 1)

Chemical reaction and diffusion for corrosion

Chemical reaction and diffusion for sulfate attack and dissolution

Moisture and heat diffusion

Chemical reaction equations for cement hydration, pozzolanic reaction, and self-healing over-all reaction

Environmental conditions and material properties

Increased /reduced permeability
Moisture content
Temperature
Cement hydration
Healing reaction
Pozzolanic reaction
Concentration of chemical species
Electrical current filed

Radial expansion of bars
Reduction of steel cross-section of bars
Reduction of physical/mechanical properties of UHDC
Aging degree,
Temperature,
relative humidity.

Assessment of serviceability limit states and prediction of the service life of structures

Mechanical model for rebars (model 2)

Material properties

Mechanics of steel bars

Stress-strain relation in the bars

Rebar necking or fracture
Bond law between concrete and steel

Mechanical model for UHDC (model 3)

Environmental conditions, mechanical loads, and material properties

Mechanics of UHDC

Stress-strain relation in the UHDC
Evolution of deformations, damage, cracking, and mechanical properties

Damage and crack localization
Load bearing capacity

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The ReSHEALience project modelling approach

Physics of the model

combines the chemical processes of binder hydration and self-healing with heat, water, oxygen and ions transport processes and corrosion

Cement (and cement substitute) hydration

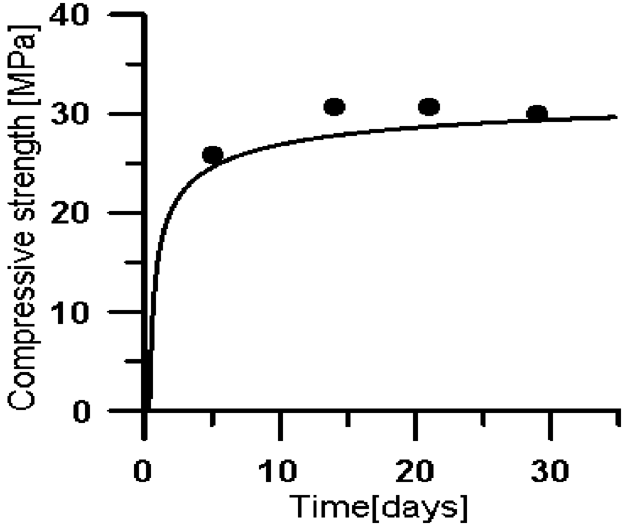
$$\frac{\partial \alpha_c}{\partial t} = A_c(\alpha_c, h)\, e^{-E_{ac}/RT}$$

$$\frac{\partial \alpha_s}{\partial t} = A_s(\alpha_s, h)\, e^{-E_{as}/RT}$$

E_{ac} hydration activation energy

α_c degree of hydration

h relative humidity



$$A_c(\alpha_c, h) = A_{c1}\left(\frac{A_{c2}}{\alpha_c^{\infty}} + \alpha_c\right)(\alpha_c^{\infty} - \alpha_c)\, e^{-\eta_c \alpha_c/\alpha_c^{\infty}}\left[1 + (a - ah)^b\right]^{-1}$$

A_{c1}, A_{c2}, a, b, η_c
parameters to be calibrated

asynptotic degree of hydration

The ReSHEALience project modelling approach

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Heat transfer $$\rho c_t \frac{\partial T}{\partial t} = -\boldsymbol{\nabla} \cdot \boldsymbol{q} + \dot{Q}_c + \dot{Q}_s$$

heat of hydration for cement and cement substitutes

Water diffusion $$-\frac{\partial w(h, \alpha_c, \alpha_s)}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{J_w}$$

water flux linked through water permeability coefficient to humidity gradient

$$\boldsymbol{J_w} = -D_h(h, T, d)\boldsymbol{\nabla} h$$

Oxygen diffusion $$-\frac{\partial C_o}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{J_o} - \boldsymbol{J_w}\boldsymbol{\nabla} C_o + \dot{O}$$

source/sink term due to chemical reactions

concentration gradient

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combines the chemical processes of binder hydration and self-healing with heat, water, oxygen and ions transport processes and corrosion

Chloride ions diffusion $-\frac{\partial C_c}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{J_c} - \boldsymbol{J_w}\boldsymbol{\nabla} C_c + \frac{\partial C_{cb}}{\partial t}$

bound chlorides concentration

free chlorides concentration

Carbon dioxide diffusion $-\frac{\partial C_{CO_2}}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{J}_{CO_2} + \dot{C}_{CO_2}$

Sulphate ions diffusion $-\frac{\partial C_s}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{J_s} - \boldsymbol{J_w}\boldsymbol{\nabla} C_s + \dot{C}_S$

Calcium ions diffusion $-\frac{\partial C_{Ca}}{\partial t} = \boldsymbol{\nabla} \cdot \boldsymbol{J_{Ca}} - \boldsymbol{J_w}\boldsymbol{\nabla} C_{Ca} + \dot{C}_{Ca}$

source/sink terms due to chemical reactions

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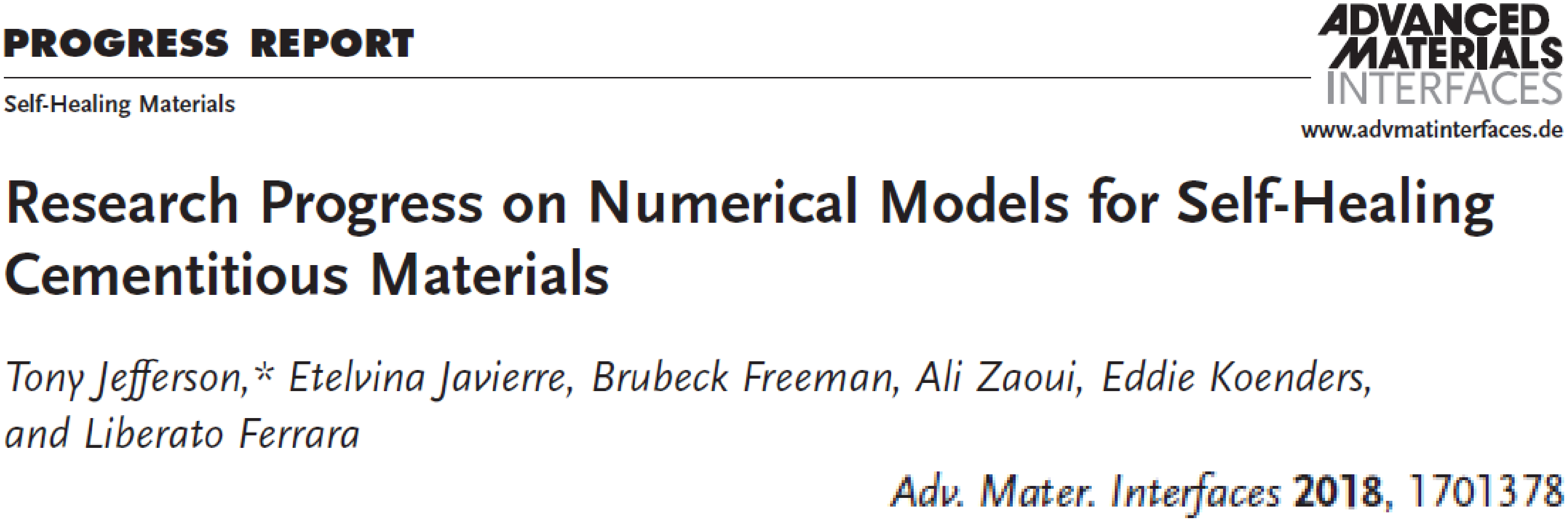
The ReSHEALience project modelling approach

Physics of the model

combines the chemical processes of binder hydration and self-healing with heat, water, oxygen and ions transport processes and corrosion

Self-healing modelling



PROGRESS REPORT

ADVANCED MATERIALS INTERFACES

Self-Healing Materials

www.advmatinterfaces.de

Research Progress on Numerical Models for Self-Healing Cementitious Materials

Tony Jefferson, Etelvina Javierre, Brubeck Freeman, Ali Zaoui, Eddie Koenders, and Liberato Ferrara*

Adv. Mater. Interfaces **2018**, 1701378

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The ReSHEALience project modelling approach

Physics of the model

combines the chemical processes of binder hydration and self-healing with heat, water, oxygen and ions transport processes and corrosion

Self-healing modelling

Cement and Concrete Composites 86 (2018) 190–205

Contents lists available at ScienceDirect

Cement and Concrete Composites

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

ELSEVIER

Numerical modeling of mechanical regain due to self-healing in cement based composites

Giovanni Di Luzio [a, *], Liberato Ferrara [a], Visar Krelani [a, b]

[a] Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
[b] University for Business and Technology, Kalabria, 10000, Prishtinë, Kosovo

$$f_h(h) = \frac{1}{1 + (a_h - a_h h)^{b_h}}$$

$$f_w(w) = \{1 - [a_w - a_w(1 - w)]^{b_w}\}^{-1}$$

$$\frac{\partial \lambda_{sh}}{\partial t} = A_{sh}(\lambda_{sh}) e^{-E_{ash}/RT}$$

$$A_{sh} = \tilde{A}_{sh}(1 - \lambda_{sh})$$

Autogenous healing analogous to cement hydration

λ_{sh} = self healing degree
A_{sh} = self healing affinity

$$\tilde{A}_{sh} = \tilde{A}_{sho}\, f_h(h)\, f_w(w)$$

$$\tilde{A}_{sho} = \tilde{A}_{sh1}\,(1 - \alpha_c^{sh0})c + \tilde{A}_{sh2}\, sh_{st-adm}$$

autogenous and stimulated healing

dependence on relative humidity *h* and crack width *w*

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The model so far does not consider:

- the water pressure: a liquid flowing faster through the crack would wash out the deposited healing products, preventing the self-healing from occurring;
- the leaching or dissolution, since an aggressive fluid that leads to a leaching or dissolution reaction can affect the healed crack;
- the stability of the crack over time, as affected by sustained through-crack stress

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The ReSHEALience project modelling approach

Model output

Coupled with a smeared crack mechanical modelling approach (microplane M5)

Galerkin space discretization of partial differential equations rewritten in weak form.

Crank–Nicolson method (a central difference method) time discretization.

When solving the aforementioned equations for diffusion and chemical processes at macroscale it is assumed that damage is constant, i.e. physical and chemical properties are controlled by mechanical properties (damage) from the previous time step as obtained in input from the mechanical model.

The output of the model is interpolated for the material description of the mechanical model, calculating the values on each element, to provide

- all the chemical quantities that characterized the hydration and self-healing;
- moisture and temperature field;
- volume expansion and reduction of physical/mechanical properties.

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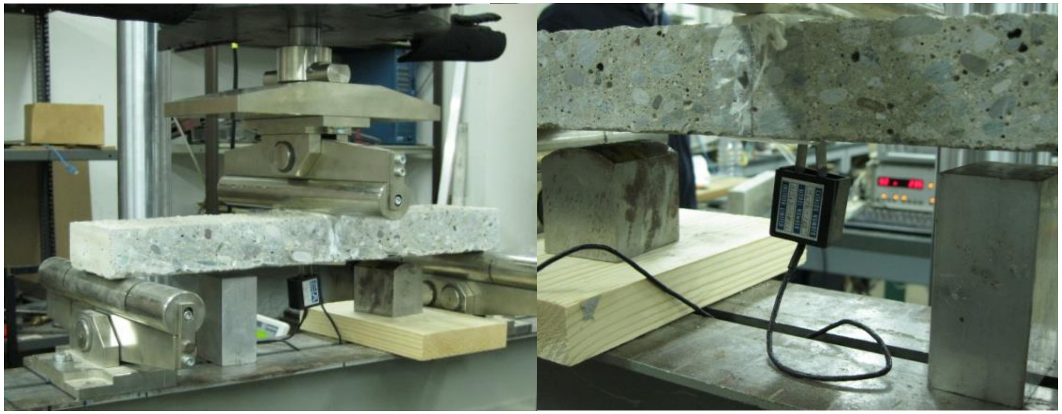
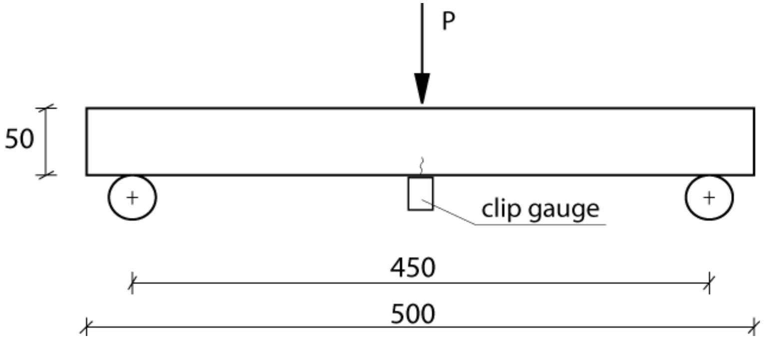
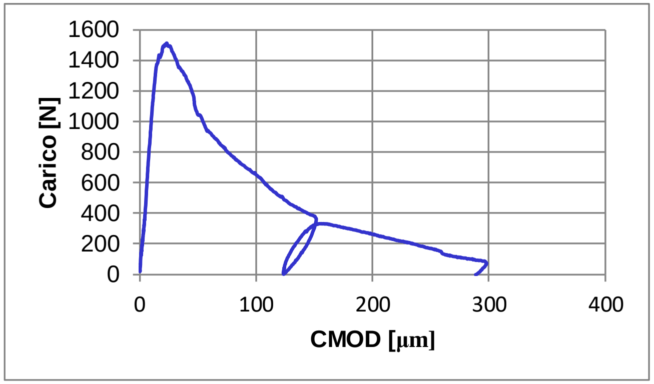
The ReSHEALience project modelling approach

Validation of the self-healing modelling

		WITHOUT ADMIXTURE	WITH ADMIXTURE
Cement	[kg/m^3]	300	300
Water	[kg/m^3]	165	165
Sand 0-8 mm	[kg/m^3]	975	975
Gravel 8-20 mm	[kg/m^3]	975	975
Superplasticizer	[lt/m^3]	3	3
Crystalline admixture	[kg/m^3]	-	3







… immersion in water and exposure to air for up to 12 months

Liberato Ferrara, Politecnico di Milano

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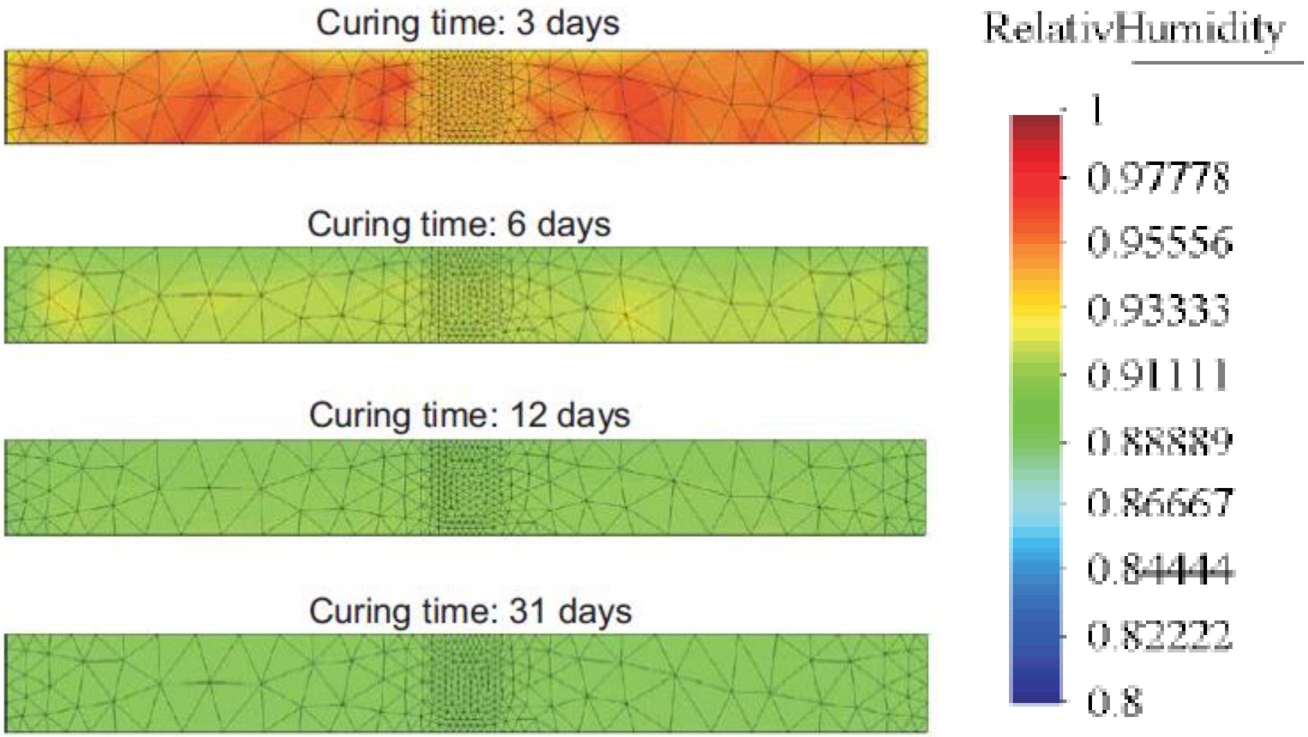
The ReSHEALience project modelling approach

Validation of the self-healing modelling

Curing - model output: relative humidity inside the specimen



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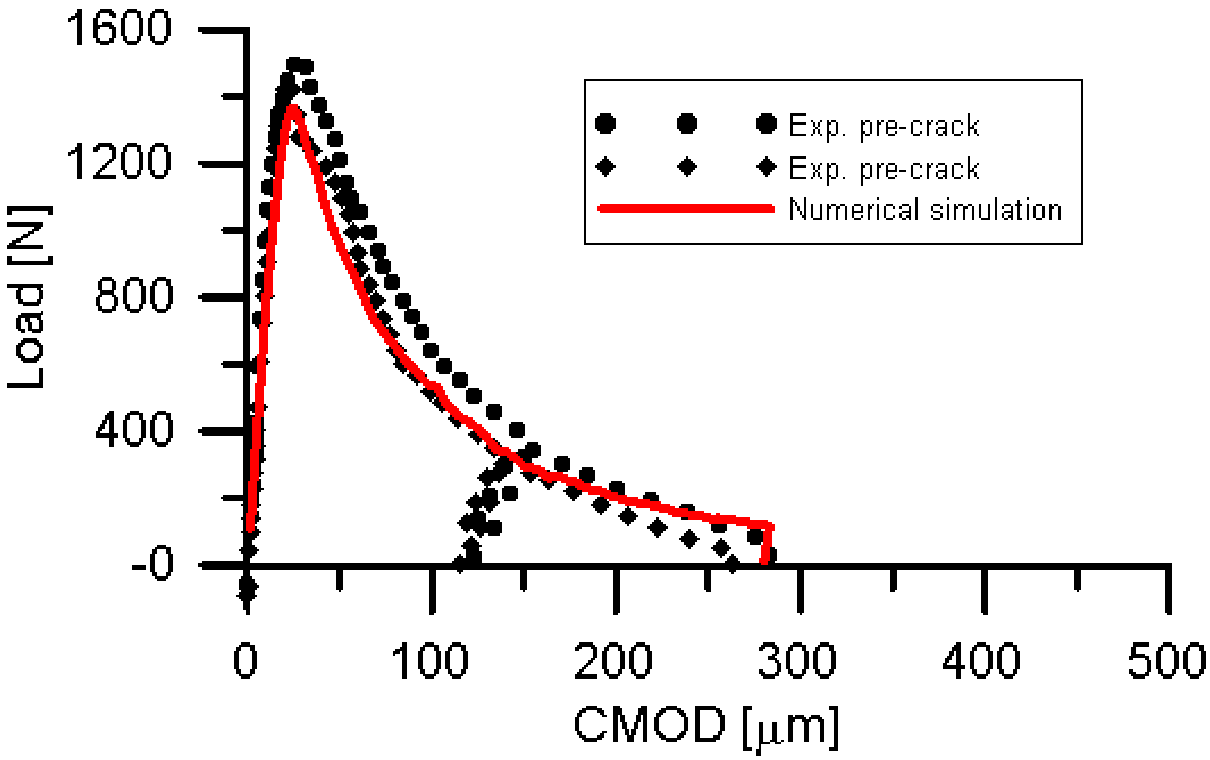
The ReSHEALience project modelling approach

Validation of the self-healing modelling

Precracking – model output: load vs. crack opening curve



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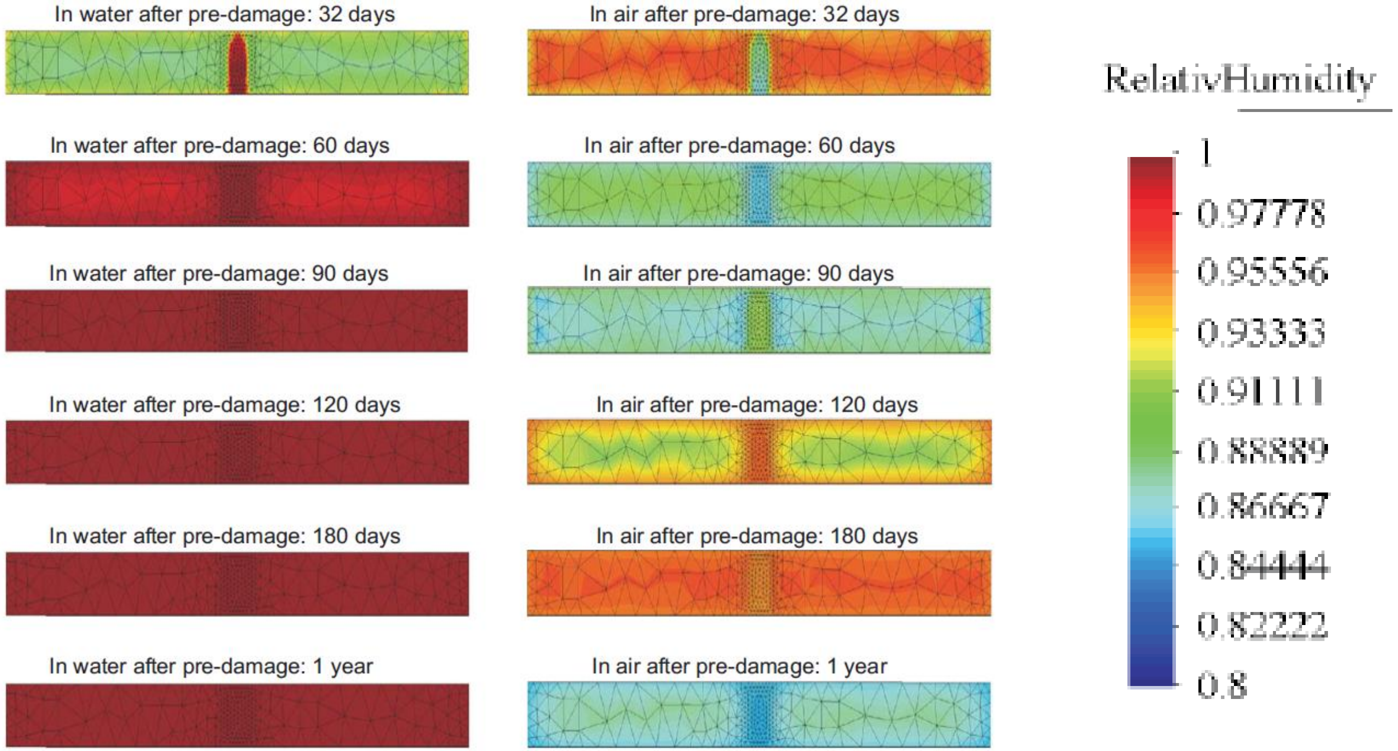
The ReSHEALience project modelling approach

Validation of the self-healing modelling

Post-cracking curing – model output: relative humidity inside the specimen



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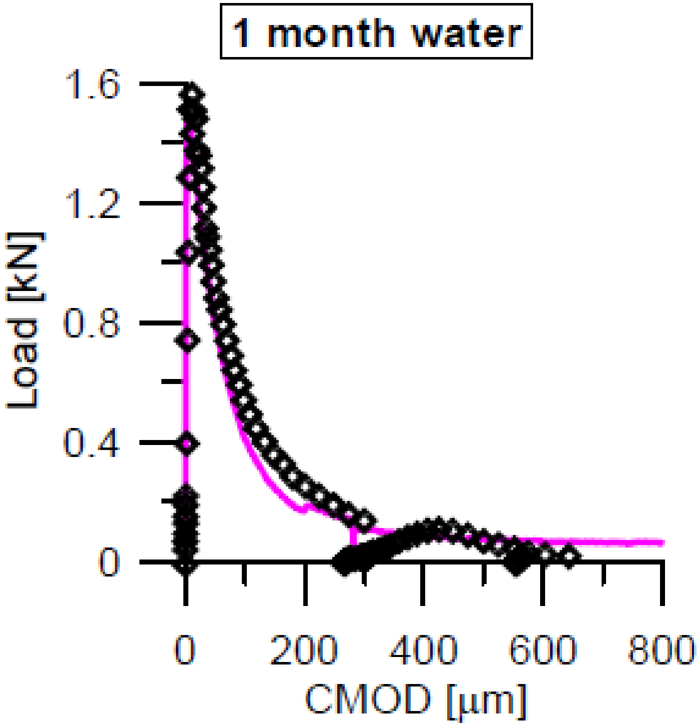
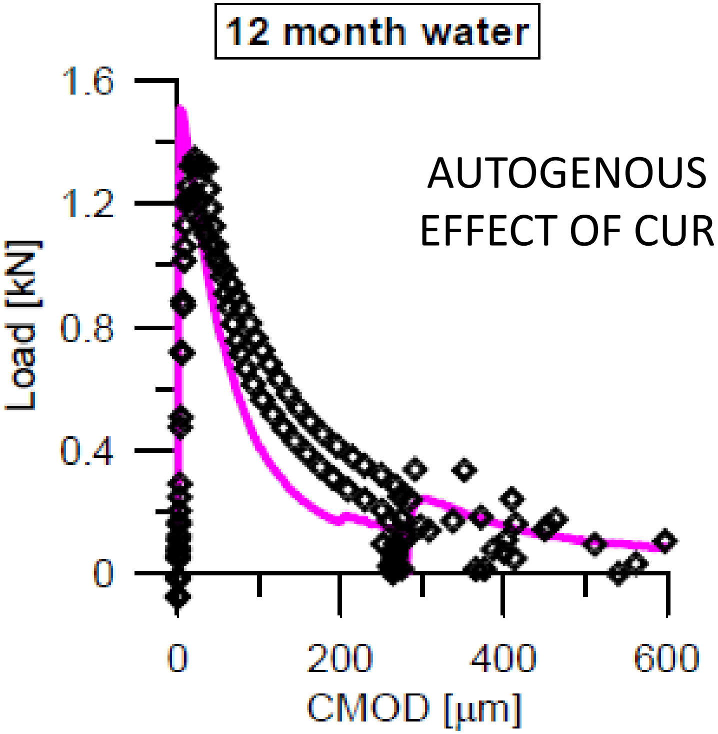
The ReSHEALience project modelling approach

Validation of the self-healing modelling

Testing to failure after healing – model output: load vs. crack opening curves





AUTOGENOUS HEALING
EFFECT OF CURING TIME

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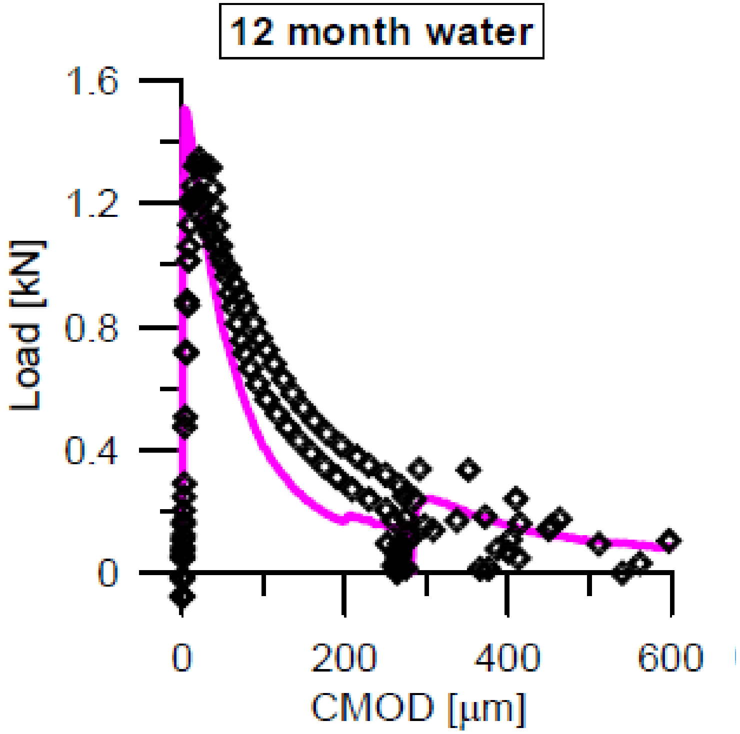
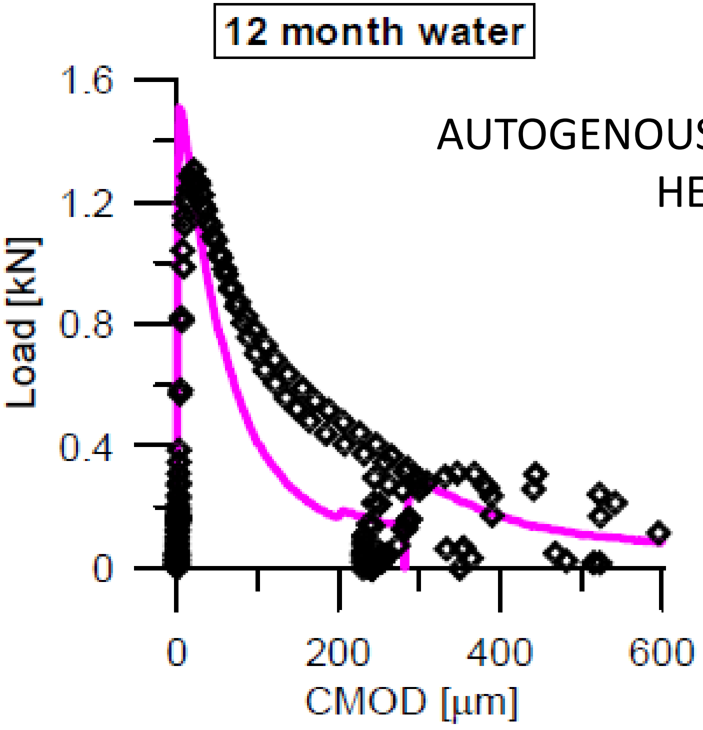
The ReSHEALience project modelling approach

Validation of the self-healing modelling

Testing to failure after healing – model output: load vs. crack opening curves





AUTOGENOUS VS. STIMULATED HEALING

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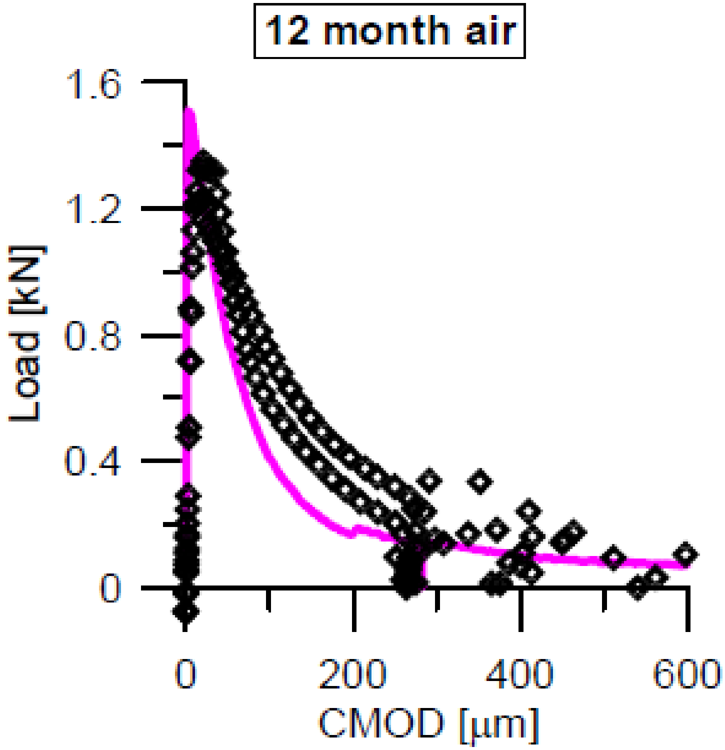
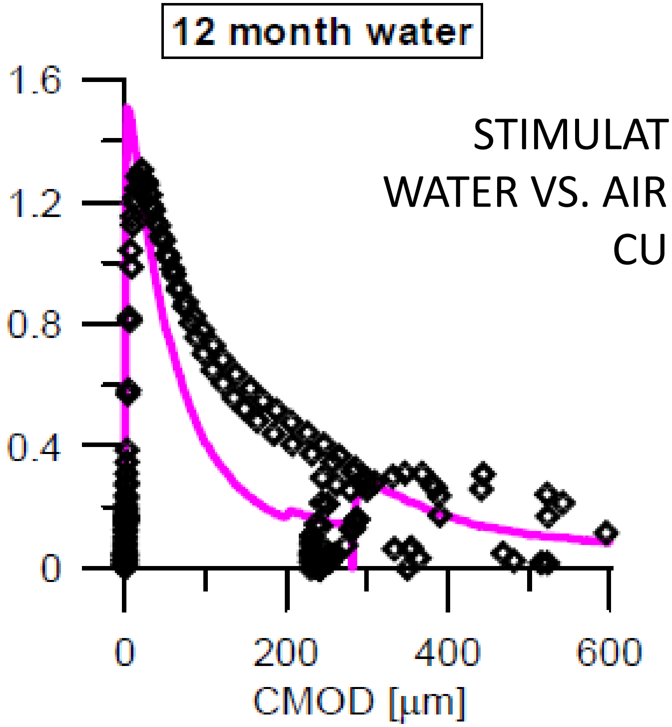
The ReSHEALience project modelling approach

Validation of the self-healing modelling

Testing to failure after healing – model output: load vs. crack opening curves





STIMULATED HEALING
WATER VS. AIR POST-CRACKING
CURING

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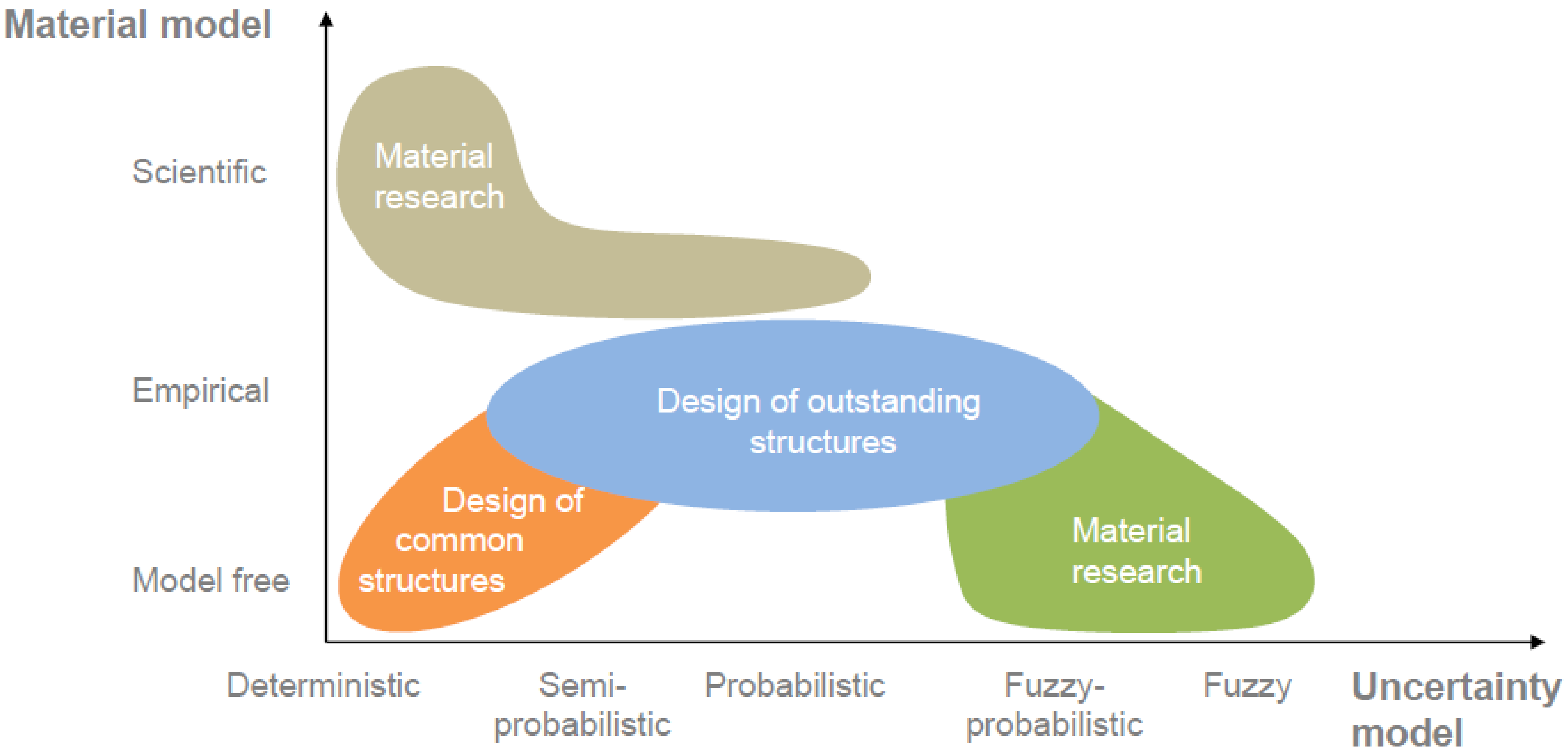
The ReSHEALience project modelling approach

… BUT …



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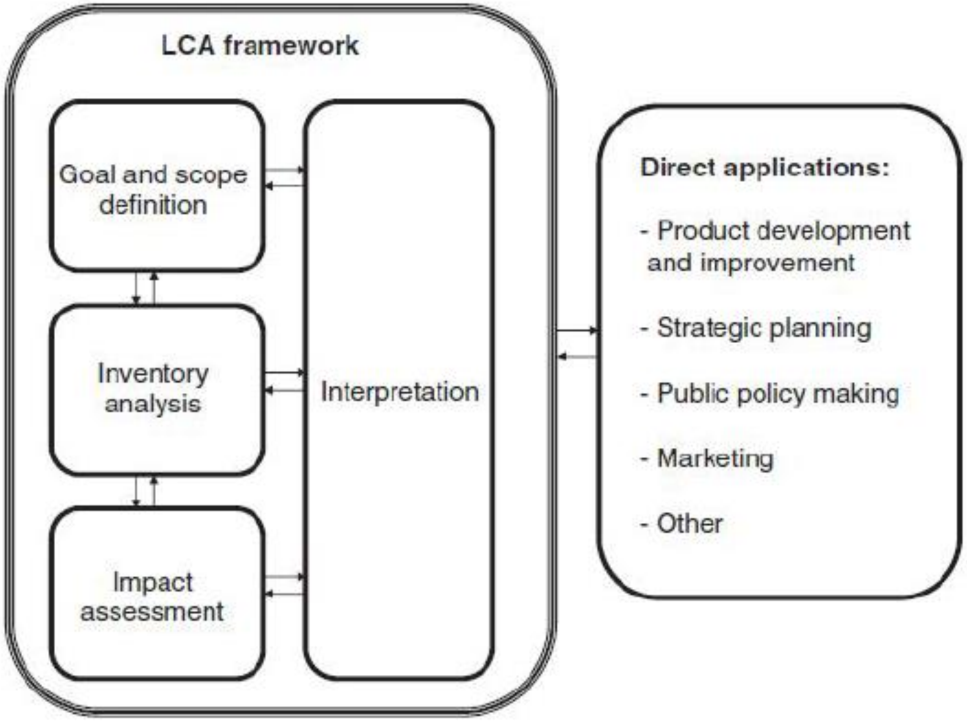
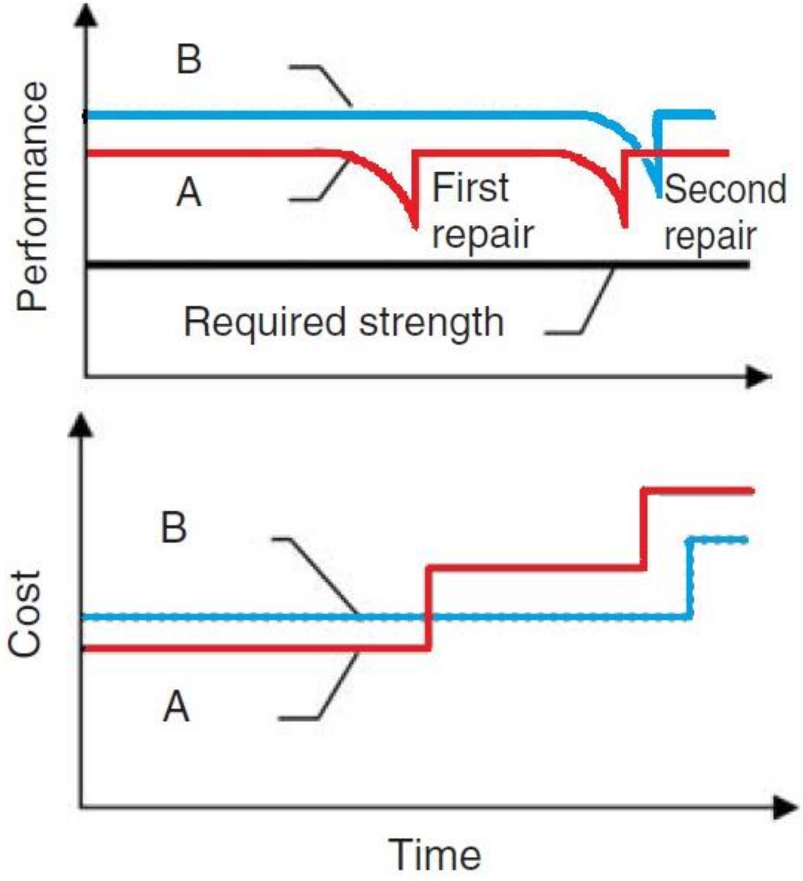
The ReSHEALience project modelling approach

… a Life Cycle Analysis approach is required …





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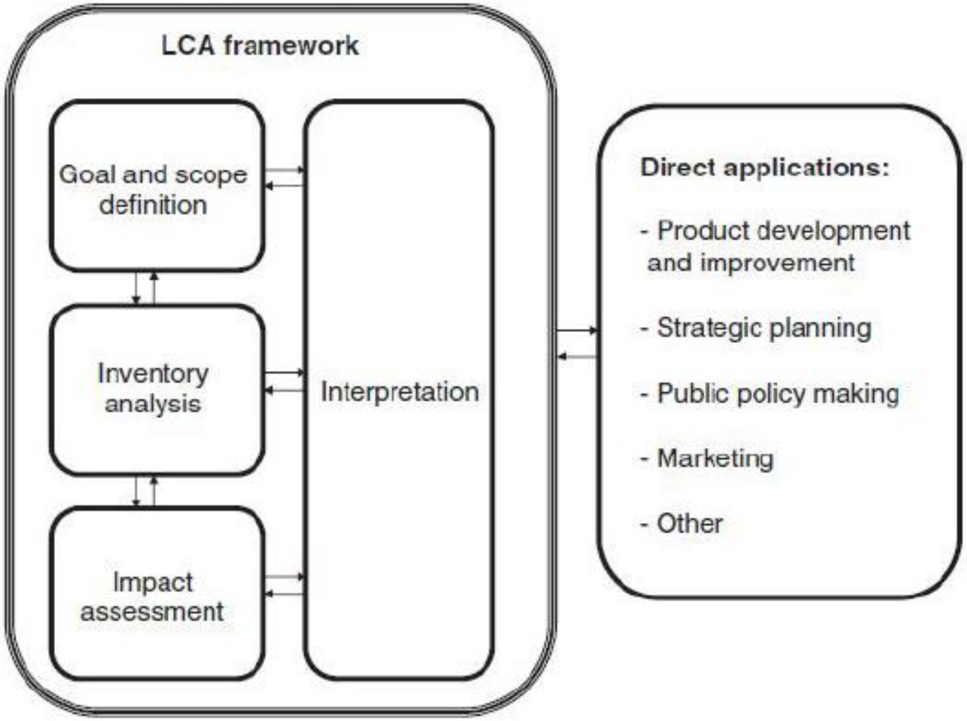
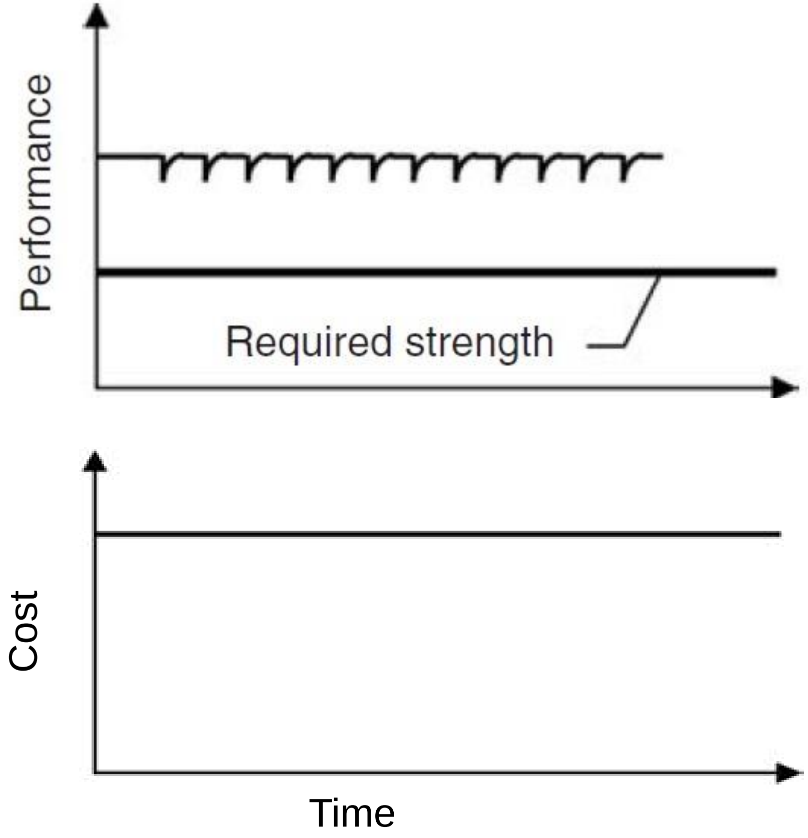
… a Life Cycle Analysis approach is required …





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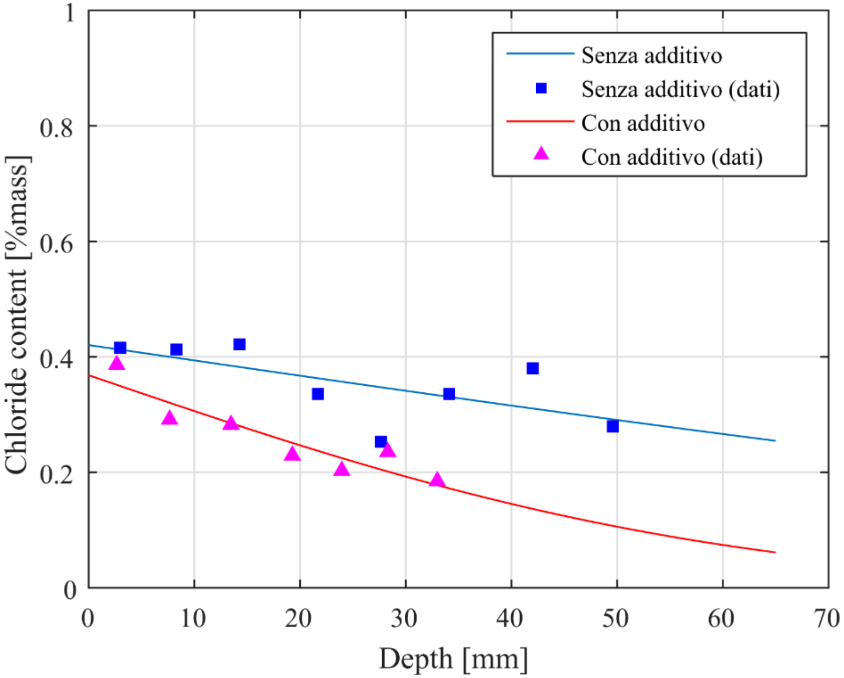
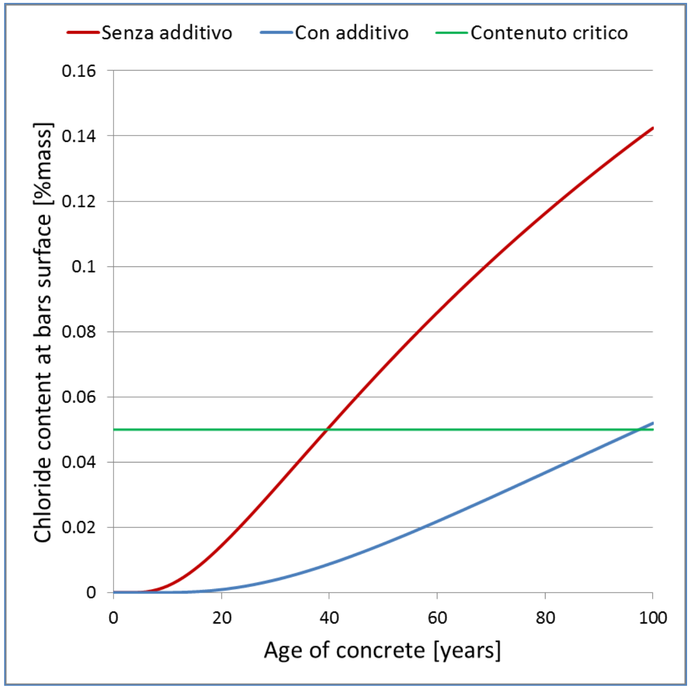
The ReSHEALience project modelling approach

… a Life Cycle Analysis approach is required …
… from durability testing to service life prediction …





$$C(x=a,t) = C_s \cdot erfc\left(\frac{x}{2\cdot\sqrt{D_{app}\cdot t}}\right)$$

$$D_{app}(t) = D_{app}(t_0)\cdot\left(\frac{t_0}{t}\right)^{\alpha}$$

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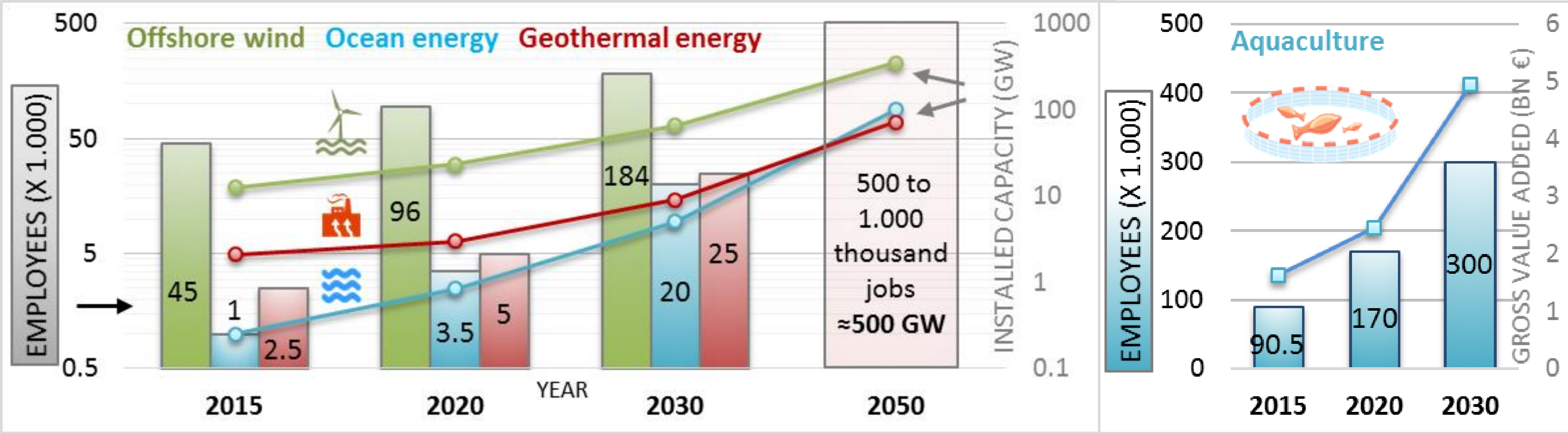
The ReSHEALience project: what next?

Ultra High Durable Concrete (UHDC):

“strain-hardening (fibre reinforced) cementitious material with functionalizing micro- and nano-scale constituents (alumina nanofibers, cellulose nanofibers/crystals, crystalline admixtures) especially added to obtain a high durability in the cracked state”.



The ReSHEALience project: what next?

Ultra High Durable Concrete (UHDC):

“strain-hardening (fibre reinforced) cementitious material with functionalizing micro- and nano-scale constituents (alumina nanofibers, cellulose nanofibers/crystals, crystalline admixtures) especially added to obtain a high durability in the cracked state”.

6 pilots: Green Energy, Blue Growth, Architectural Heritage Conservation

Cooling towers water basins (IT)
Geothermal drilling muds basins (IT)

Floaters for offshore wind towers (ES)
Mussel farming rafts (ES)
Breakwater elements (IE)

r/c retrofitting (MT)

www.uhdc.eu

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THANK YOU FOR YOUR ATTENTION

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