A Life Cycle Holistic Perspective for Nanofunctionalized UHPC Structures in Aggressive Environments: Building Better, for Longer, with Less

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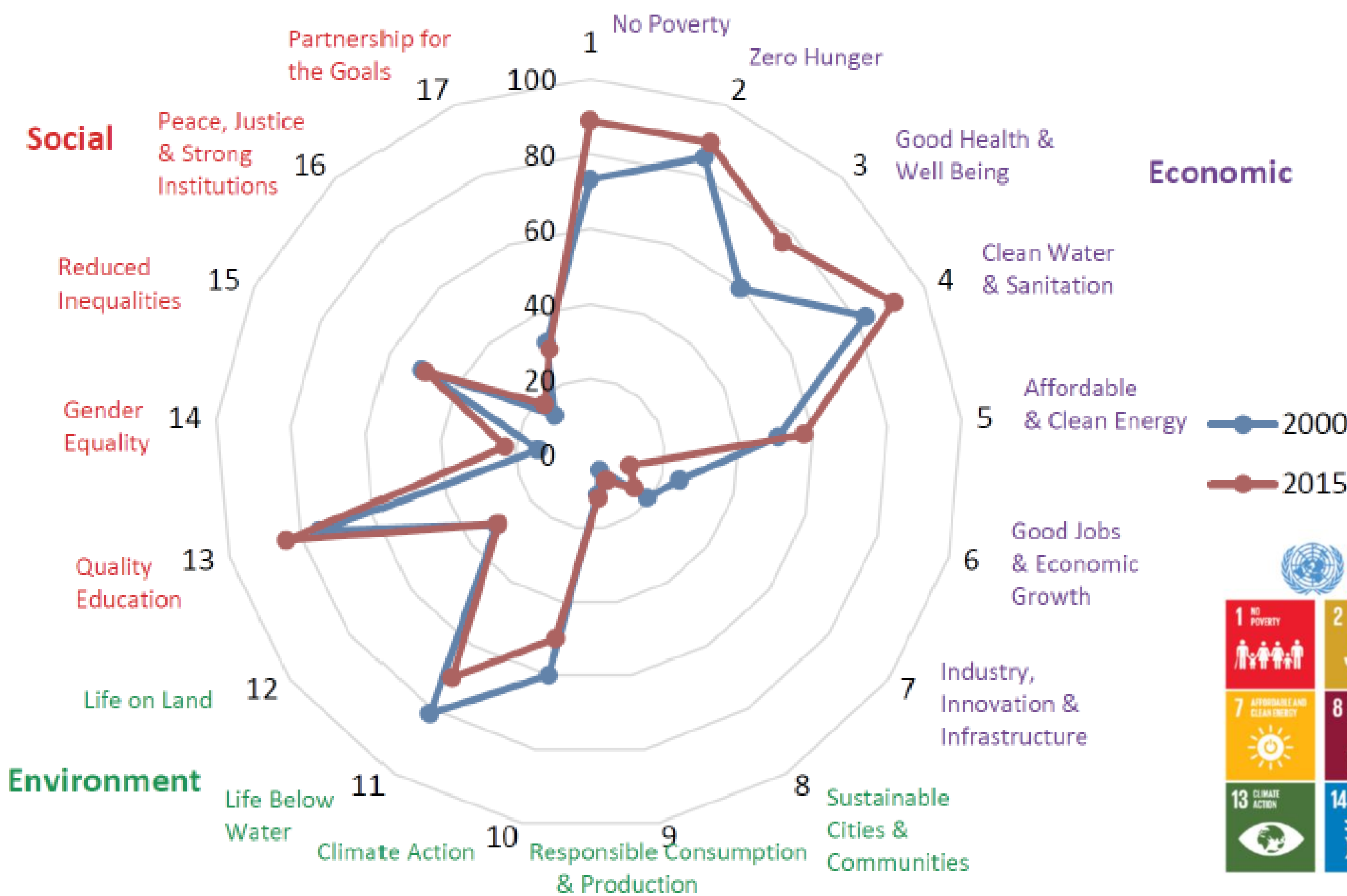
Nele de Belie

Magnel Laboratory for Concrete Research, Ghent University

Current «societal» challenges for civil engineering



Barbier and Burgess. 2017. The sustainable development goals and the systems approach to sustainability. Economics, 11.

Current «societal» challenges for civil engineering

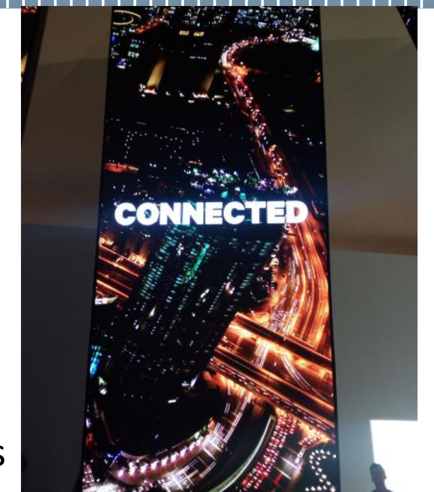
Current «societal» challenges for civil engineering

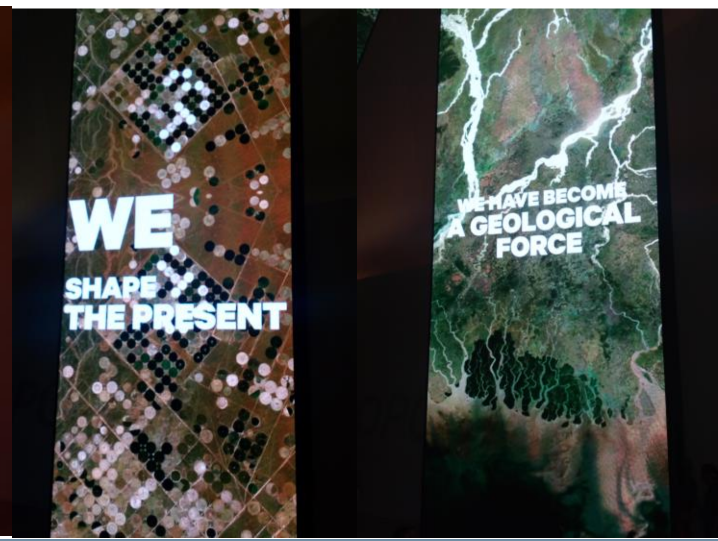
WHICH SCENARIO?

55% world population lives in urban areas
(up to 80% in high income countries)

Every year about 1% of current world population (75 mln) relocates to urban areas

Within 2045 67% of the world population will live in urban areas





Current «societal» challenges for civil engineering

WHICH SCENARIO?

CONCRETE: … a remarkably good building material
made with locally available constituents and raw materials
ideal candidate for tailored "scenario-based" solutions

10 bln tons each year: the second largest used material worldwide
twice as much than the total of all other building materials
10 bln tons/year concrete: 4 bnl t/y cement and 48 bln t/y aggregates

«IF YOU REPLACE CONCRETE WITH ANOTHER MATERIAL, IT WOULD HAVE A BIGGER CARBON FOOTPRINT»

Current «societal» challenges for civil engineering

Reduce CO_2 from clinker production

↓

Reduce clinker in cement

↓

Reduce cement in concrete

↓

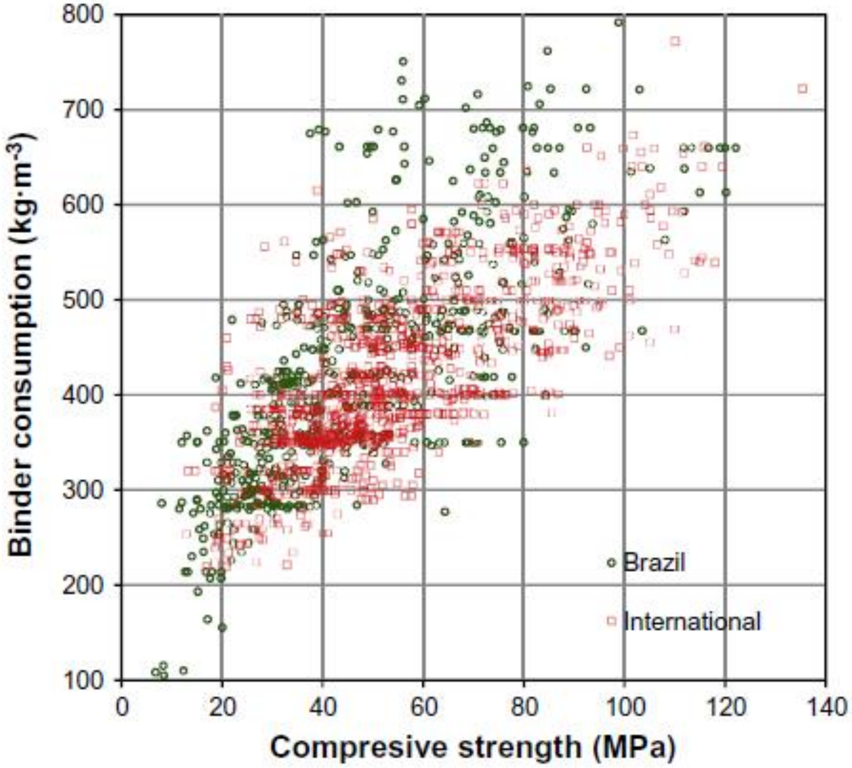
Reduce concrete in buildings and structures

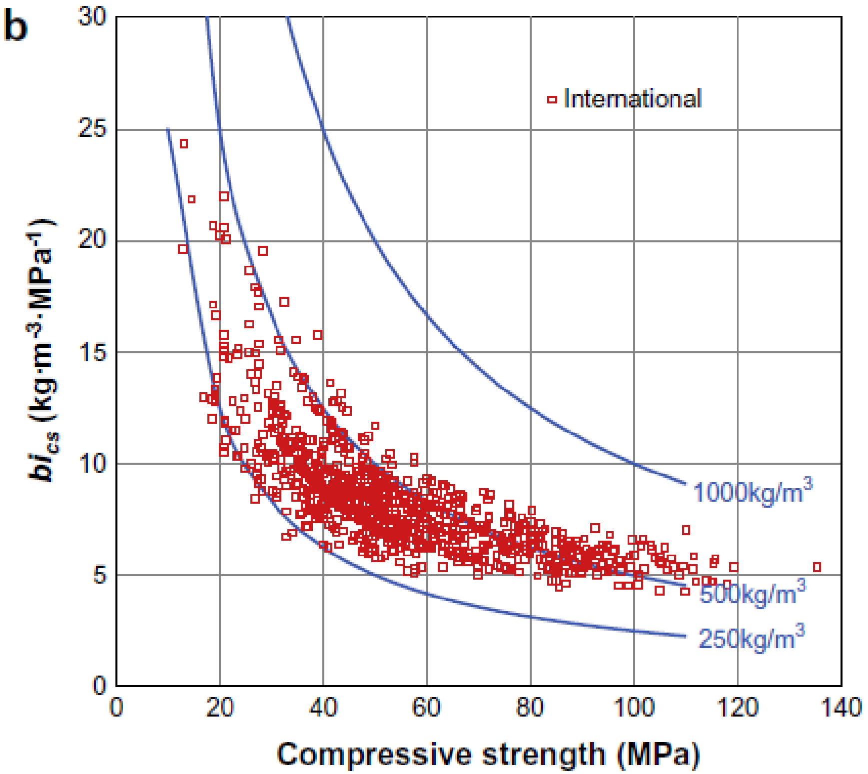
↓

More efficient (re) use of buildings and structures

Current «societal» challenges for civil engineering

WHICH PERFORMANCE? WHICH METRICS?





Damineli et al., CCC, 2010

Current «societal» challenges for civil engineering

Transportation Infrastructures :

1% GDP investment in infrastructures results into +1.5% GDP in 4 years

http://ec.europa.eu/growth/sectors/construction/index_en.htm

Every year road interruptions and traffic congestion delays cost an average of EUR 4000 to each household!

Current «societal» challenges for civil engineering

Transportation Infrastructures :

1% GDP investment in infrastructures results into +1.5% GDP in 4 years

http://ec.europa.eu/growth/sectors/construction/index_en.htm

Current «societal» challenges for civil engineering

Coastal protection: Europe has a 66000 km coastaline (3 times as much the one of US)

Coastal defense infrastructure market: 660 bn€/y + 4% year growth foreseen

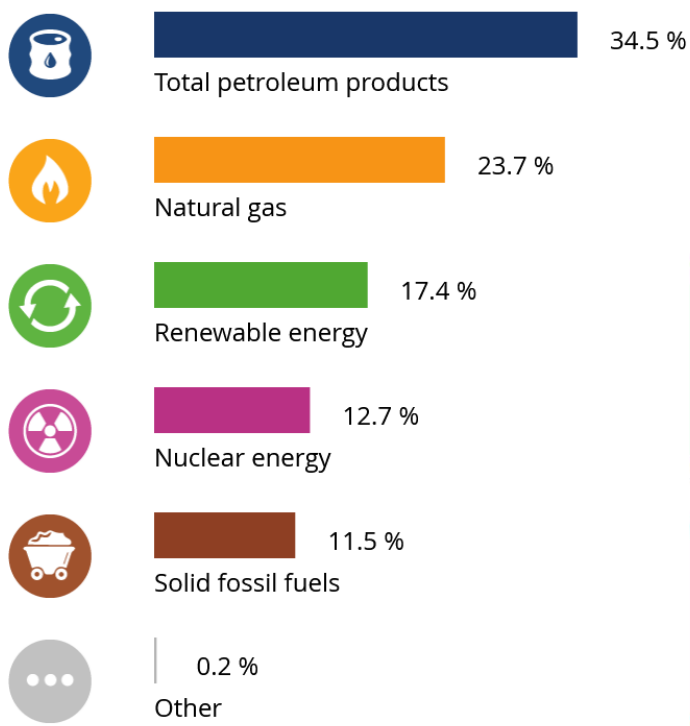
a very likely increase of the European average 100-year extreme sea level of 34–76 cm under a moderate mitigation scenario, and of 58–172 cm under a high emissions scenario

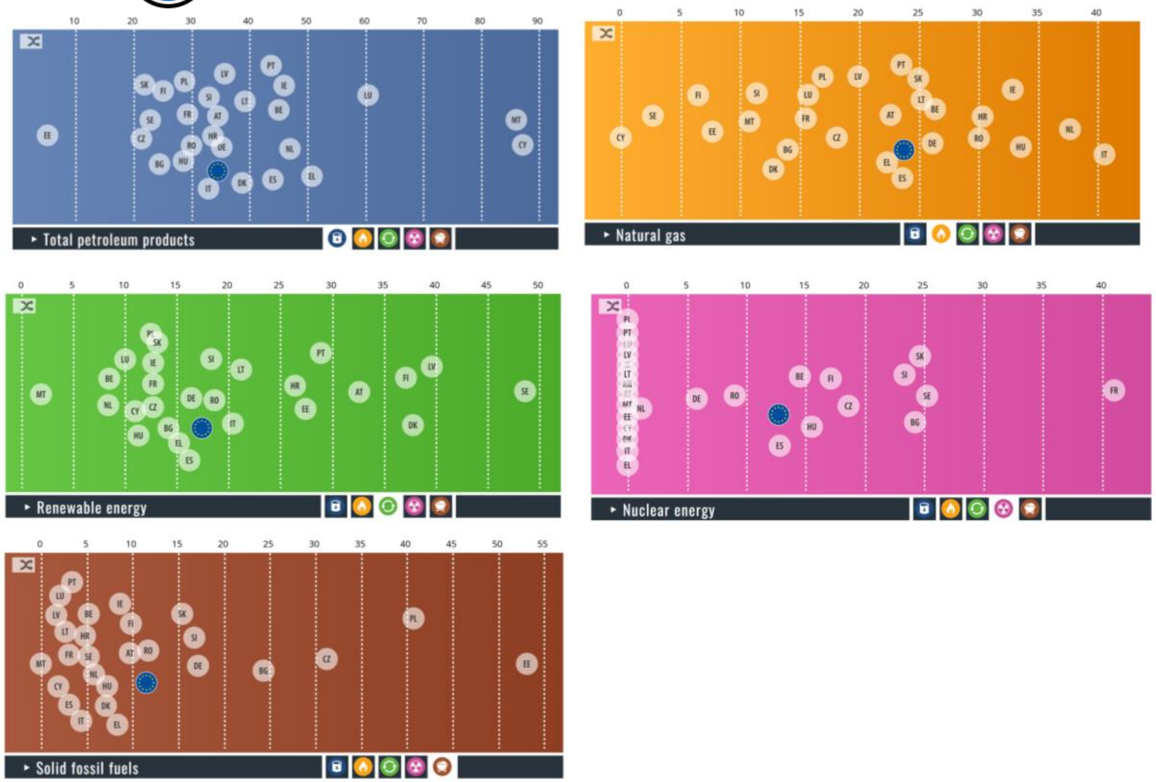
Nearly 700000 EU citizens exposed to coastal flooding

Current «societal» challenges for civil engineering

https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html

Energy mix for the European Union



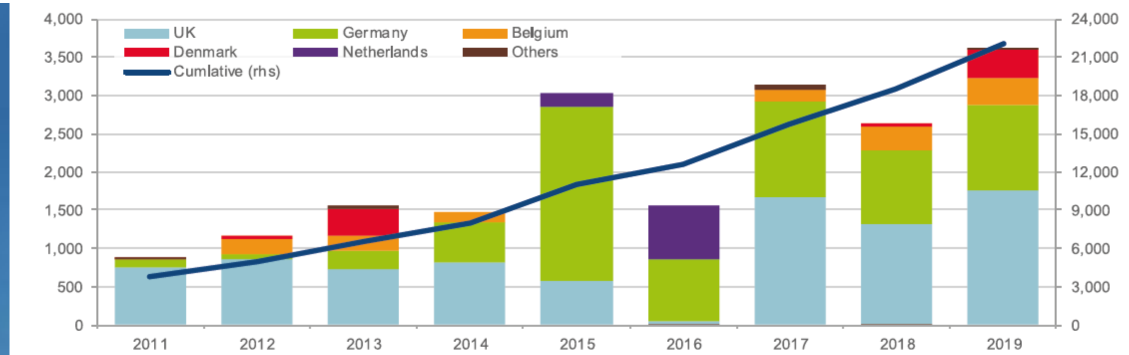


Current «societal» challenges for civil engineering

Green growth: promoting the growth of clean energy production

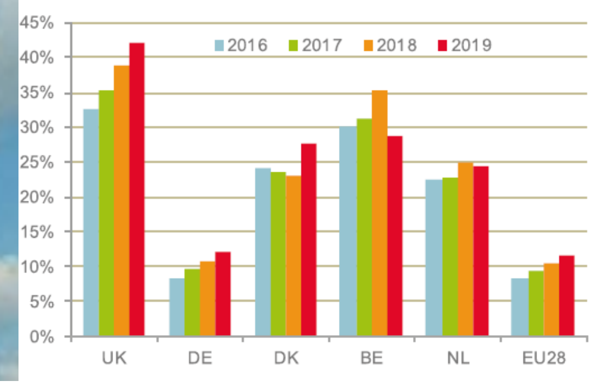
Offshore wind

https://ec.europa.eu/maritimeaffairs/policy/blue_growth_en



Note: Other Member States include Sweden, France, Spain, Ireland and Portugal.
Source: JRC, GWEC, WindEurope.

Ratio of offshore over total wind energy, percentage

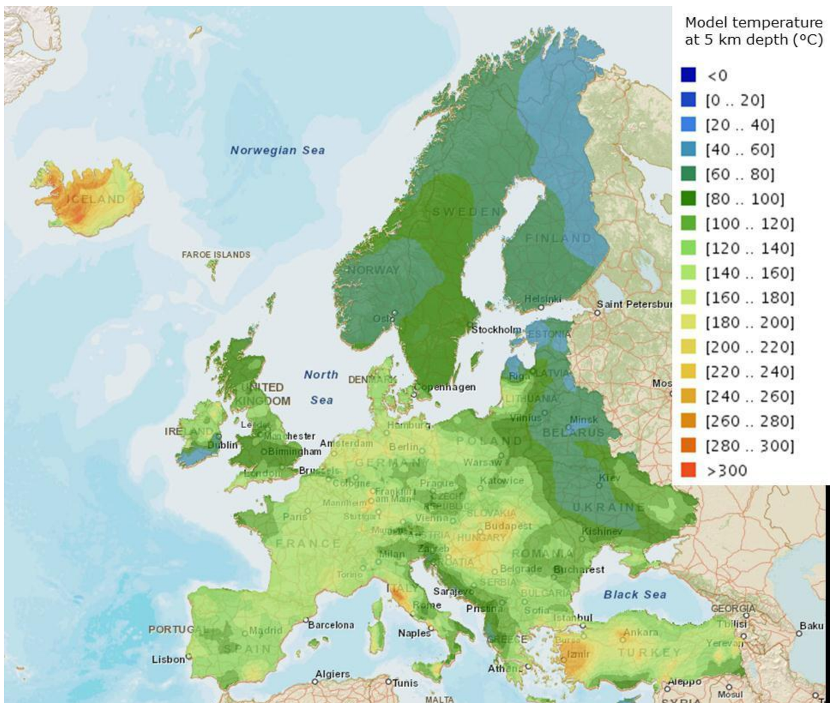


Current «societal» challenges for civil engineering

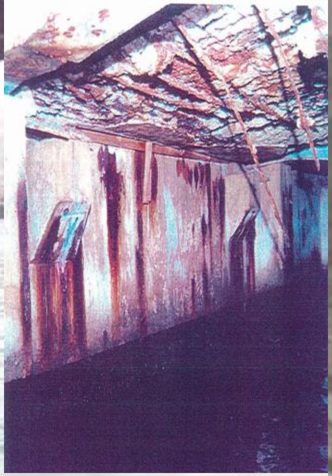
Green growth: promoting the growth of clean energy production

EGS: engineered geothermal system - stimulating deep hot resources that are otherwise not exploitable - provided technological challenges are overcome, the installed capacity of EGS technology could reach between 1200 GW to 12000 GW worldwide (currently it is 60 GW)

https://ec.europa.eu/jrc/en/news/new-report-analyses-geothermal-energy-sector



Current «societal» challenges for civil engineering



	Maximum w/c	minimum cement content	minimum compressive strength	minimum concrete cover	maximum crack width
		kg/m^3	MPa	mm	mm
XS	0.40 - 0.65	300 - 400	25 - 40/50	25 – 75	0.1 - 0.4
XA	0.45 - 0.65	275	25/30 to 40/50	-	0.1 - 0.3
		325			
		325			

YEARLY COST OF CORROSION: 2.5 USD TRILLION (3.4% WORLD GDP)

The ReSHEALience project challenge

The challenge

Improved material durability in buildings and infrastructures, including offshore

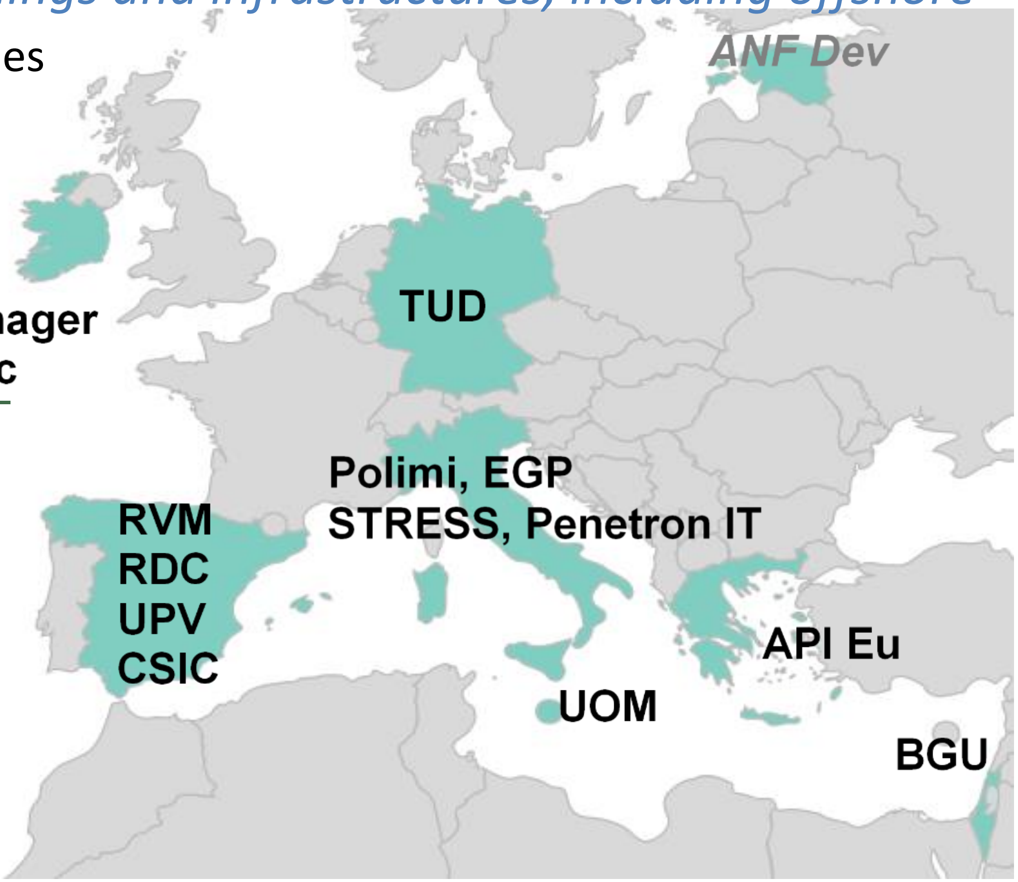
13 (+1) partners + 3 LTPs from 7 (+1) countries

5.5 M€

RESHEALIENCE

Ultra High Durability Concrete

JANUARY 1 2018 → **MARCH 31 2022**



The «ReSHEALience» project consortium

COORDINATOR

POLITECNICO MILANO 1863

Material production SMEs

PENETRON TOTAL CONCRETE PROTECTION

API Europe

NAFEN

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

TECHNISCHE UNIVERSITÄT DRESDEN

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

L-Università ta' Malta

Ben-Gurion University of the Negev

Universities and research centers

The whole value-chain of concrete construction industry

Large scale end user

enel Green Power

rover MARITIME

Infrastructure project and construction

stress

Engineering consultancy - SME

BANAGHER PRECAST CONCRETE

RDC

Precast concrete construction and engineering consultancy - SME

The «SMARTINCs» project consortium

Durability & sustainability

Structure design

Concrete technology

Self-healing agents

Processes & modeling

R&D — innovation — market

UNIVERSITEIT GENT

CSIC

UNIVERSIDAD DE CÓRDOBA

POLITECNICO MILANO 1863

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

TU Delft

KU LEUVEN

RDC

KIT Karlsruhe Institute of Technology

cstc.be

PENETRON

fib CEB-FIP

concrefy fresh thinking for construction

CUGLA Concrete Solutions

BESIX

Buzzi Unicem

Politecnico di Torino

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UNIVERSITY OF CAMBRIDGE

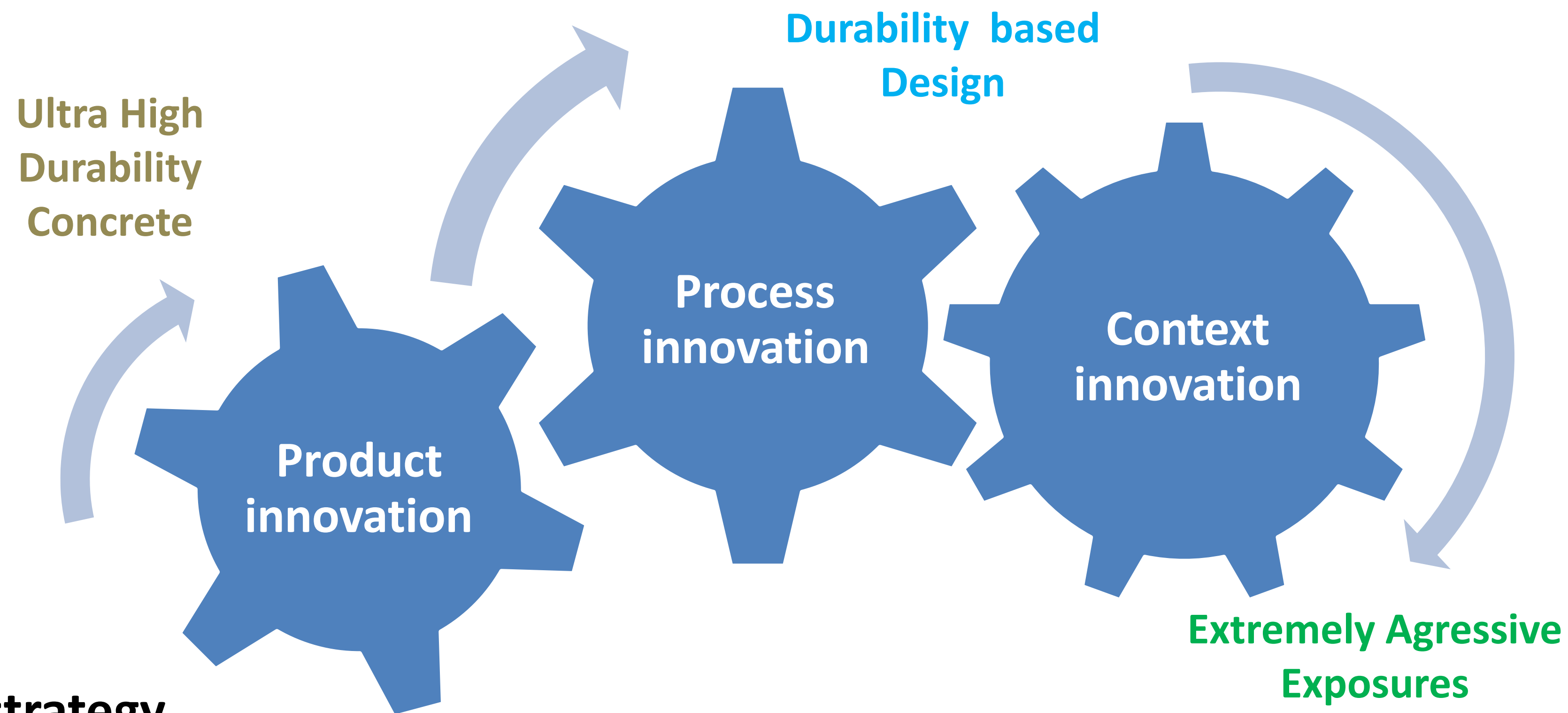
BCCA

Avecom Bioproducts & Apps

Micropore Technologies

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860006.

The strategy



The strategy

Develop a Ultra High Durability Concretes (**UHDCs**) and a methodology for Durability modelling of materials and Durability Assessment-based Design of buildings and structures to improve durability and predict their **long-term performance** under Extremely Aggressive Exposures

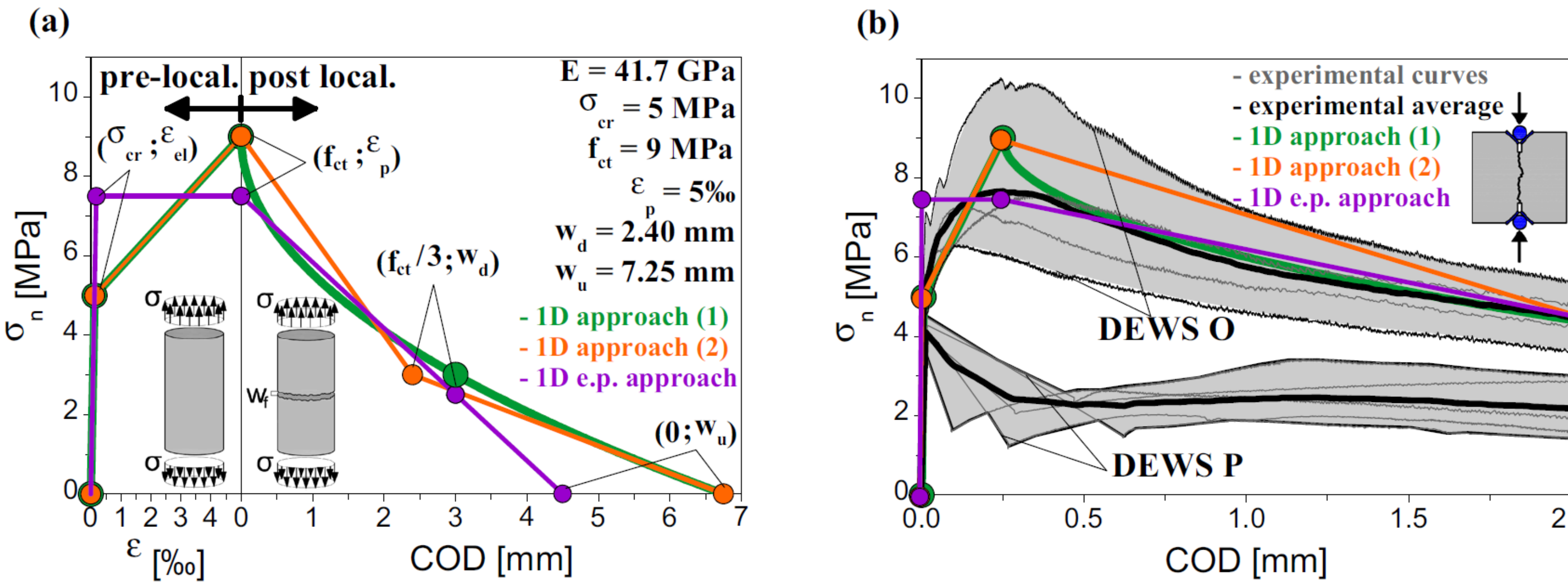
The strategy
Material innovation: UHPC

Ultra High Durability Concrete (UHDC): *"strain-hardening fibre/textile reinforced cementitious material with micro- and nano-scale functionalizing constituents, especially added to obtain a high durability in the cracked state under extremely aggressive exposure conditions".*

"if you replace concrete/cement-based materials with any other construction material … it will have a bigger CO2 footprint!".

The strategy
Material innovation: UHPC

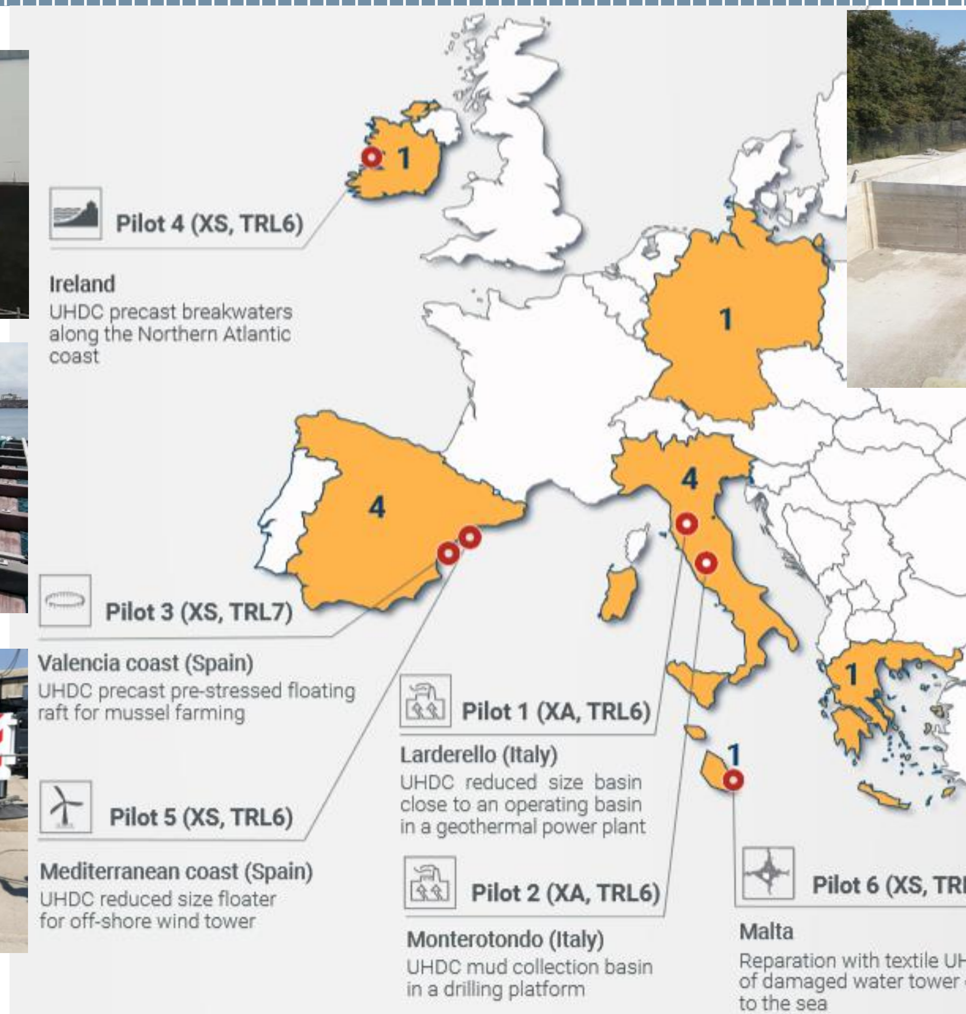
How do we identify design material parameters for UHDC ?
DEWS test results: calibrate a direct tension model curve
and simulate 4pb tests on thin and deep beams



Lo Monte and Ferrara, M&S 2020

The strategy
Process innovation: upscaling

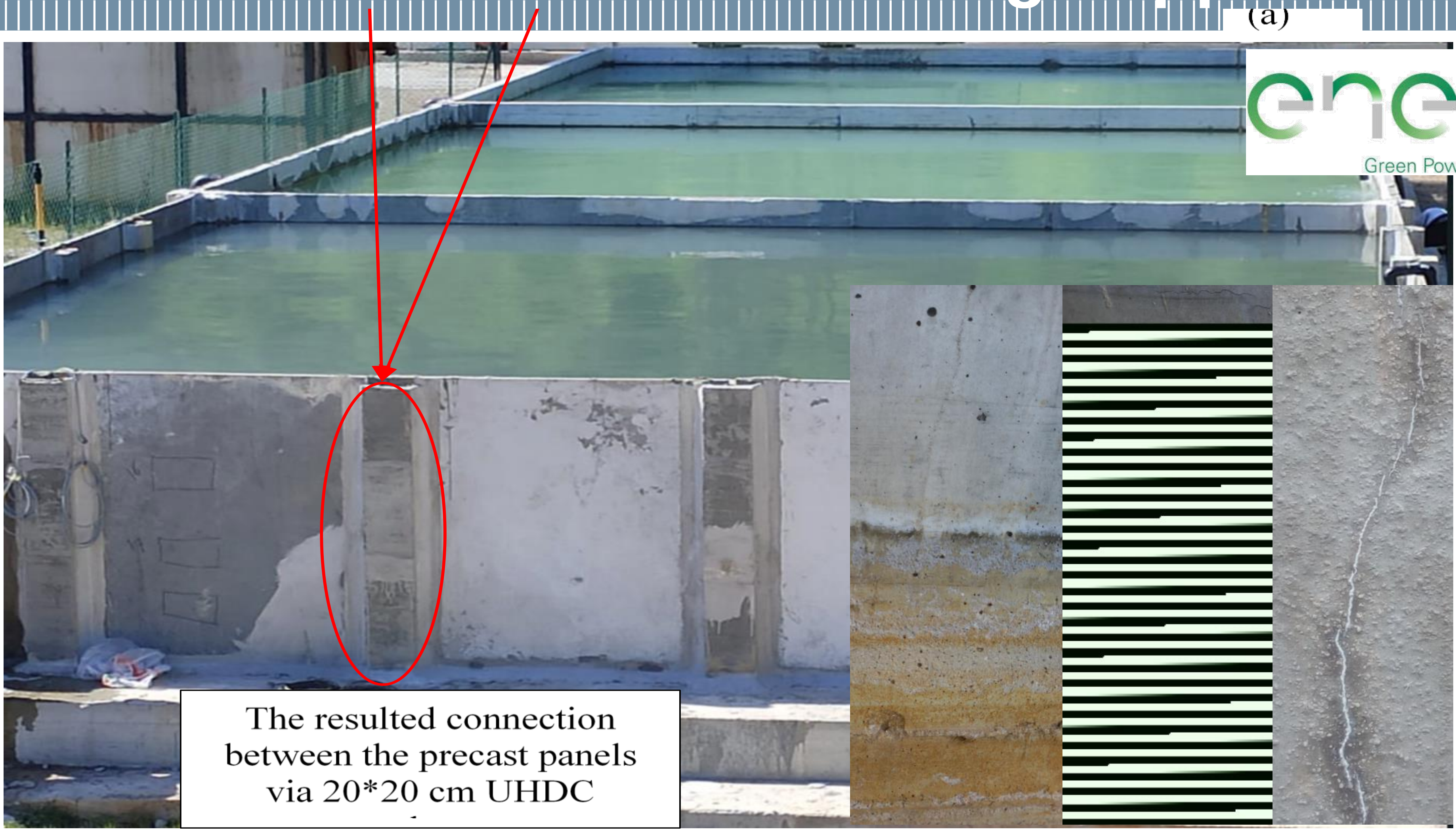
The ReSHEALience project strategy - Context innovation: 6 full scale pilots



The ReSHEALience project strategy: towards a novel holistic design approach

Green Power

The ReSHEALience project strategy: towards a novel holistic design approach



The ReSHEALience project strategy: towards a novel holistic design approach

Reduce cement in concrete?

350 kg/m3 cement
10 cm thickness
35 kg/m^2 cement

600 kg/m^3 cement
500 kg/m3 slag
3 cm thickness
18 kg/m^2 cement
15 kg/m^2 slag

Reduce concrete in structures!

The ReSHEALience project strategy: towards a novel holistic design approach

Constituents	XA-CA	XA-CA _CEMIII	XA-CA +ANF	XA-CA +CNC	XA-CA +CNF
CEM I 52,5 R	*600*	-	*600*	*600*	*600*
CEM III	-	*600*	-	-	-
Slag	*500*	*500*	*500*	*500*	*500*
Water	*200*	*200*	*200*	*200*	*200*
Steel fibers Azichem Readymesh 200	*120*	*120*	*120*	*120*	*120*
Sand 0-2mm	*982*	*982*	*982*	*982*	*982*
Superplasticizer Glenium ACE 300	*33*	*33*	*33*	*33*	*33*
Crystalline admixtures	*3*	*3*	*3*	*3*	*3*
*Alumina nanofibers**	-	-	*0.25*	-	-
*Cellulose nanocrystals**	-	-	-	*0.15*	-
*Cellulose nanofibrils**	-	-	-	-	*0.15*

* *% by cement mass*

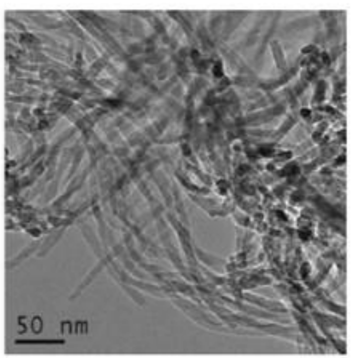
What nanos can do?

The ReSHEALience project strategy: towards a novel holistic design approach

NAFEN
Enhancing the world with nano

Alumina nanofibres

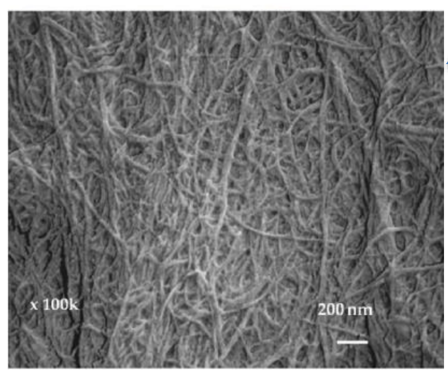
Nanofibers content (by weight) [ISO 3251]	10%
Particle size [SEM]	Diameter: 4-11 nm Length: 100-900 nm
Surface area [BET]	155 m²/g
Dispersion basis	Deionized Water
pH [ASTM D1293]	6.4 – 7.8



PENETRON
TOTAL CONCRETE PROTECTION

Crystalline admixture

- Porosity reducer
- ↓ water penetration under pressure
- Anti-shrinkage agent
- Self-healing promoter



API Europe

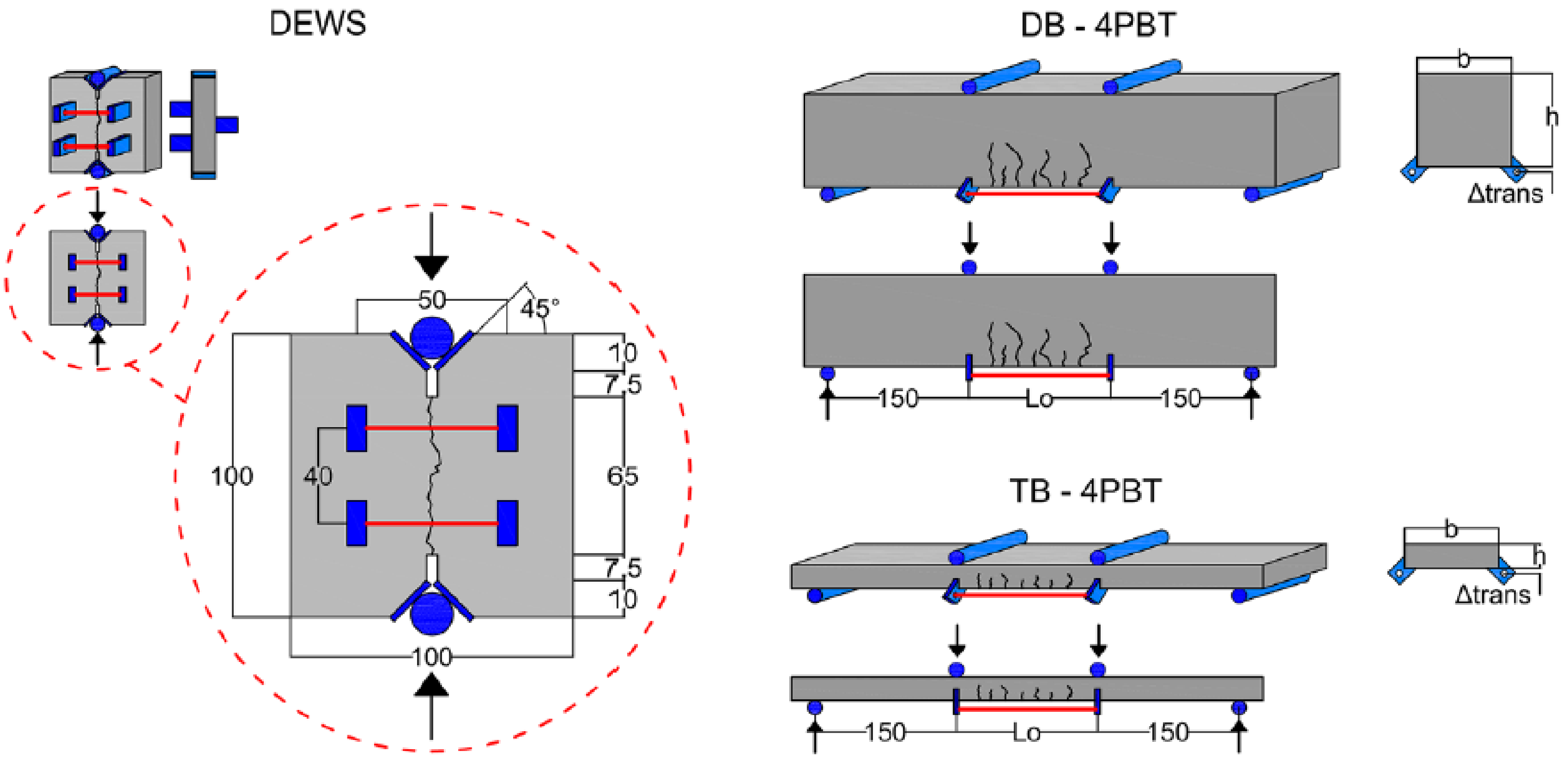
Cellulose nanocrystals

BioPlus CNC [TAPPI T412 Moisture in pulp, paper and paperboard]	Flexible
Particle size [SEM/TEM]	4-5 nm diameter, 50 – 500 nm length
Media	Water
Crystallinity [XRD]	97%
Appearance	Paste

Cellulose nanofibrils

BioPlus CNF [TAPPI T412 Moisture in pulp, paper and paperboard]	Flexible
Particle size [SEM/TEM]	5-200 nm diam., 500 nm - µm length
Media	Water
Crystallinity [XRD]	88%
Appearance	Paste

The ReSHEALience project strategy: towards a novel holistic design approach



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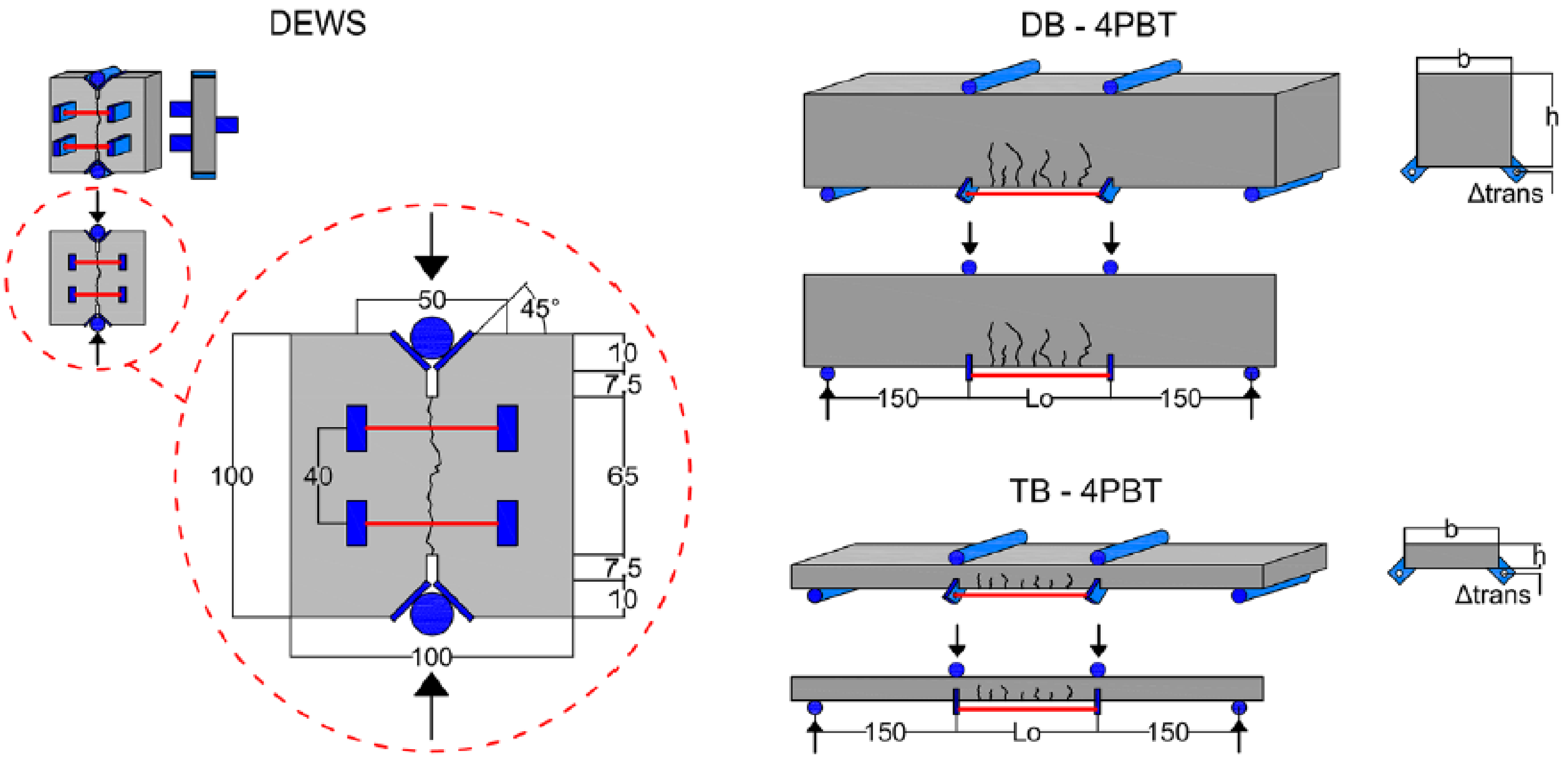
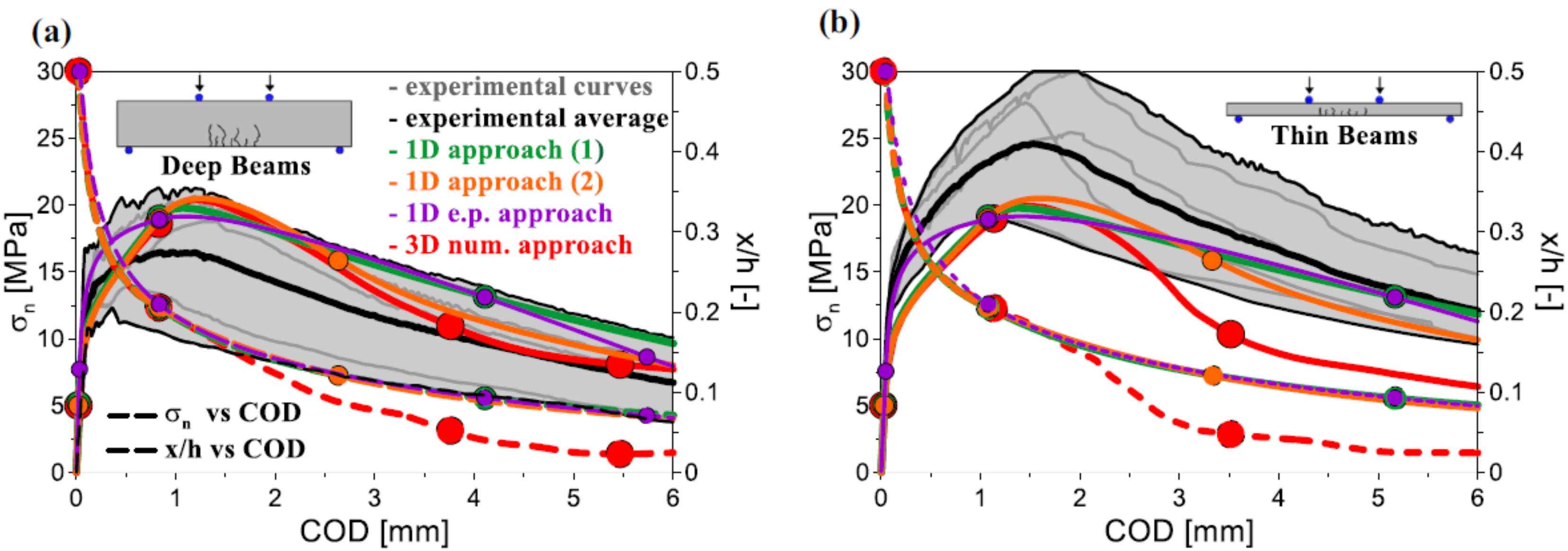


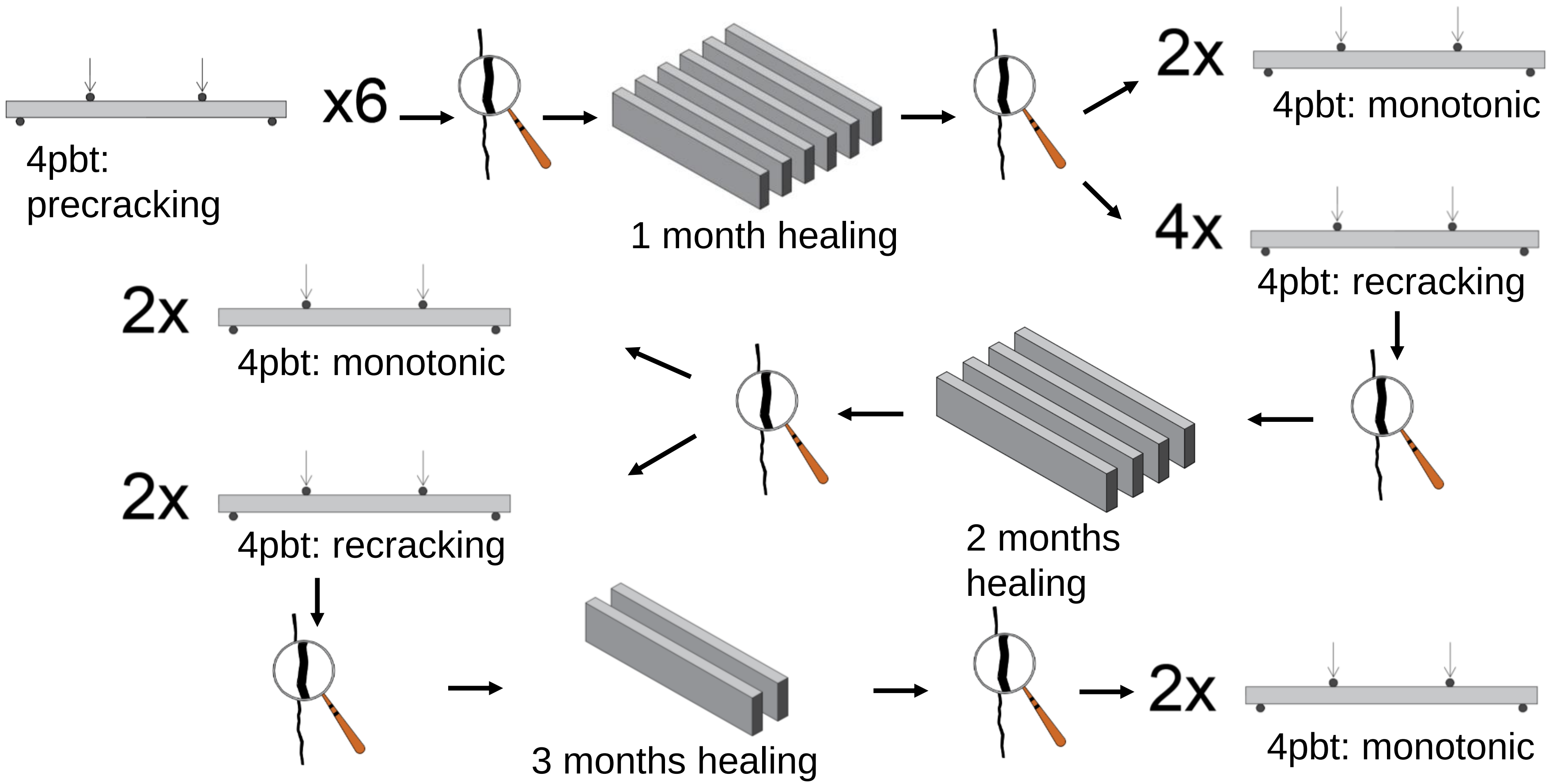
Liberato Ferrara, Department of Civil and Environmental Engineering

The ReSHEALience project strategy: towards a novel holistic design approach



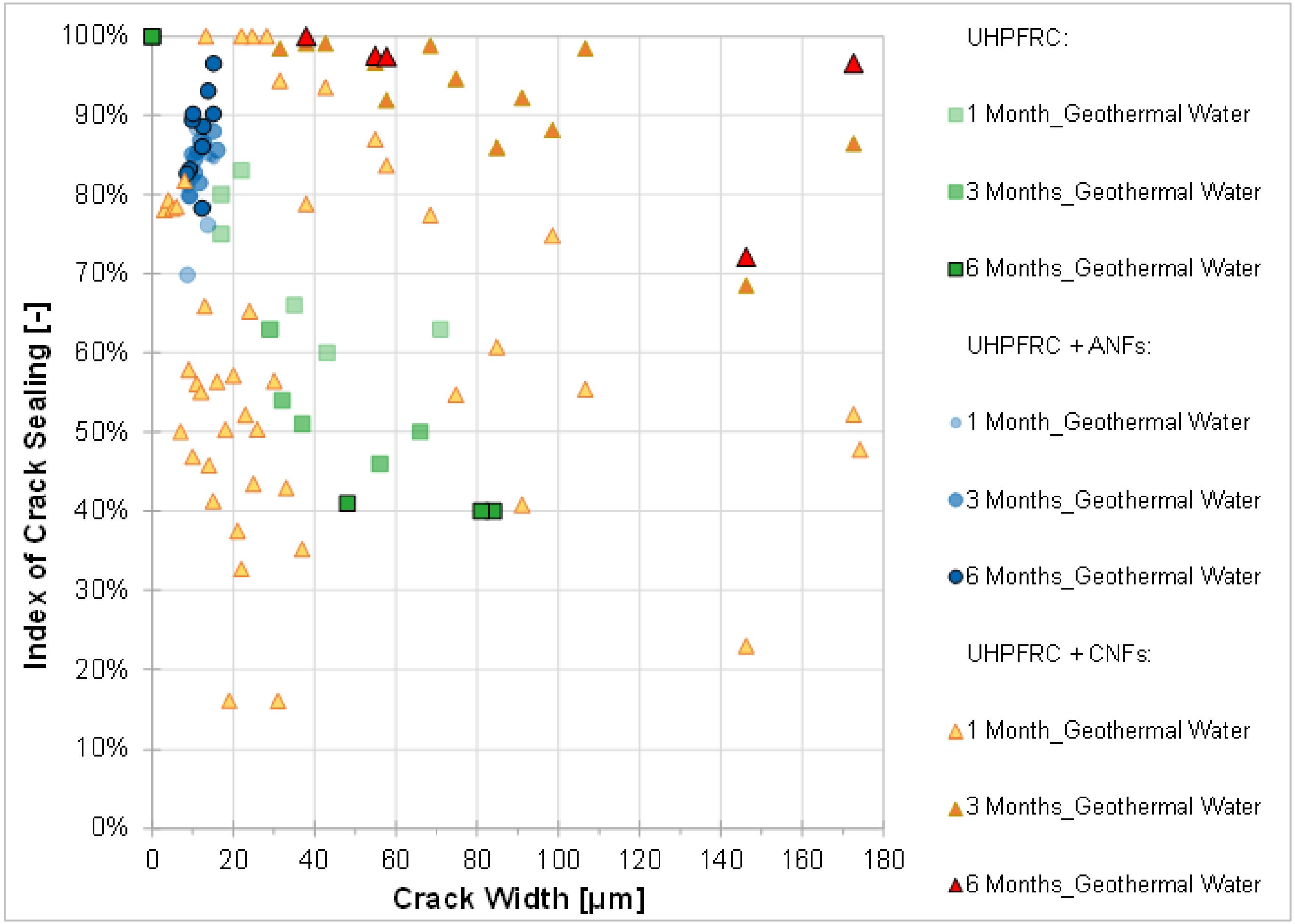
MIX ID	Min/average/Max n° of cracks	Average crack spacing (mm)
Reference	2/7/12	30
Alumina nanofibres	9/12/15	17
Cellulose nanofibrils/crystals	6/7/9	21

The ReSHEALience project strategy: towards a novel holistic design approach



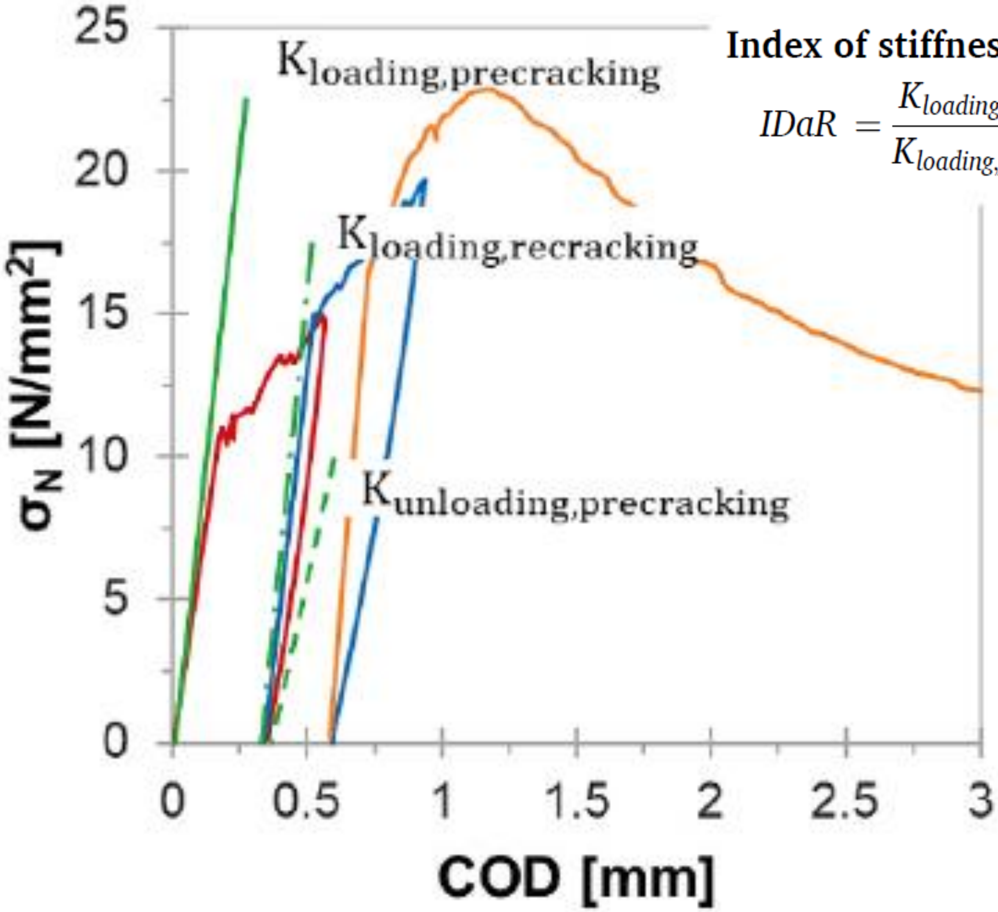
$$\text{Index of Crack Sealing ICS} = 1 - \frac{A_{crack,t}}{A_{crack,0}}$$

The ReSHEALience project strategy: towards a novel holistic design approach



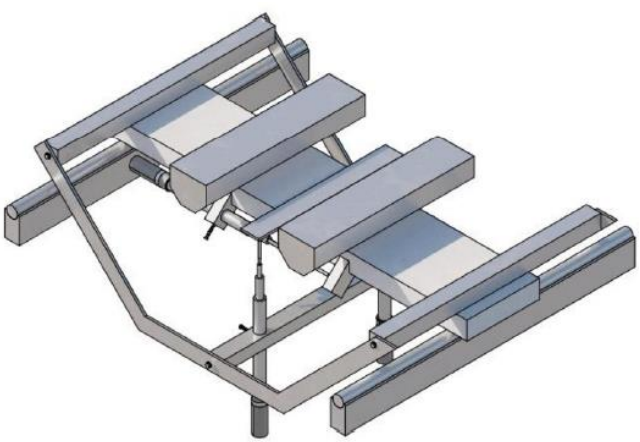
Cuenca et al.
CBM 2021
CCC 2022
Materials 2022
CBM 2023

The ReSHEALience project strategy: towards a novel holistic design approach



Index of stiffness/Damage Recovery (IDaR)

$$IDaR = \frac{K_{loading,recracking} - K_{unloading,precracking}}{K_{loading,precracking} - K_{unloading,precracking}}$$



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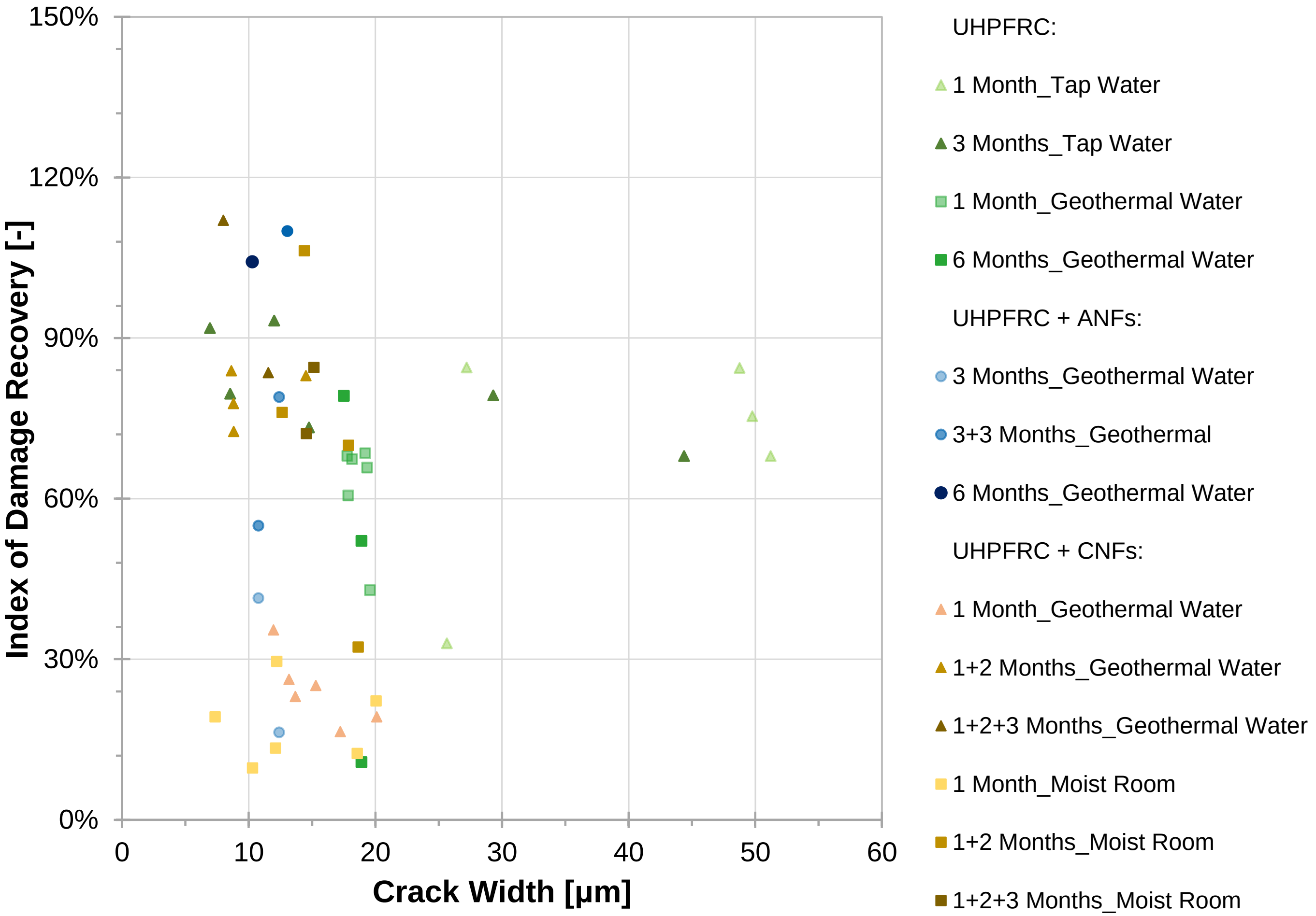

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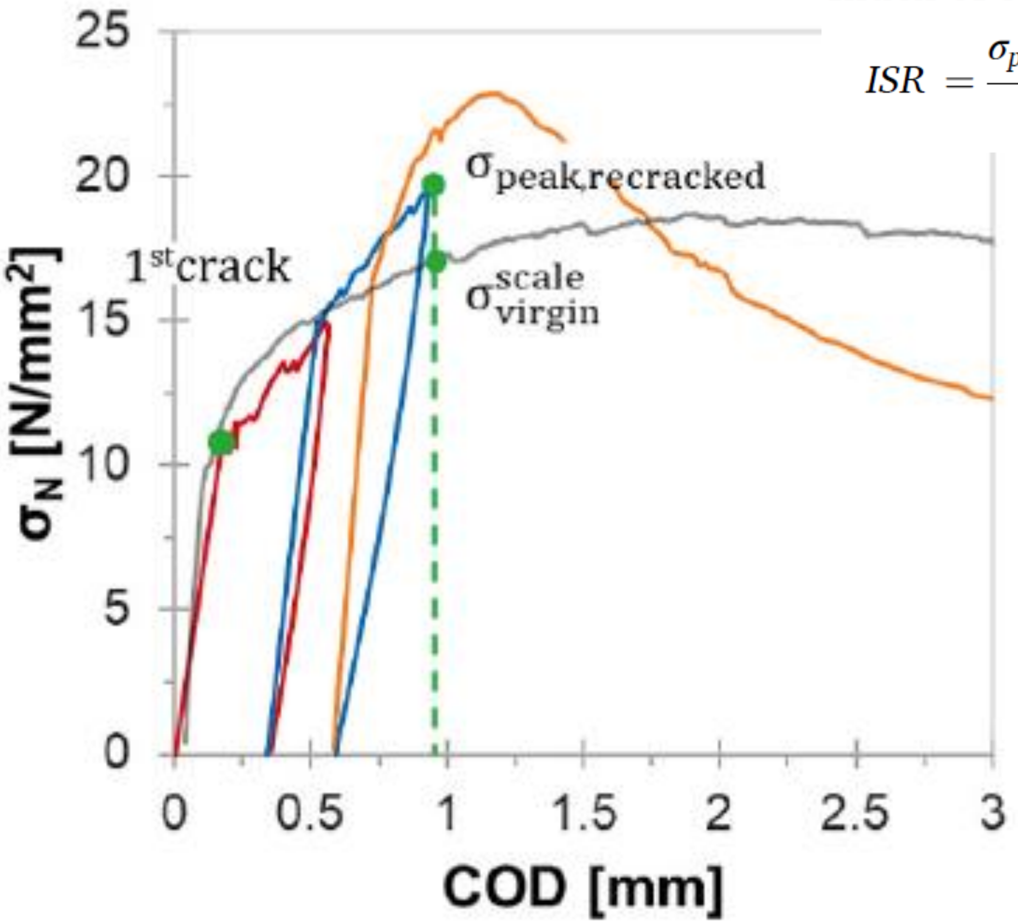

Index of Stress Capacity Recovery (ISR)

$$ISR = \frac{\sigma_{peak,recracked} - \sigma_{virgin}^{scale}}{\sigma_{virgin}^{scale}}$$

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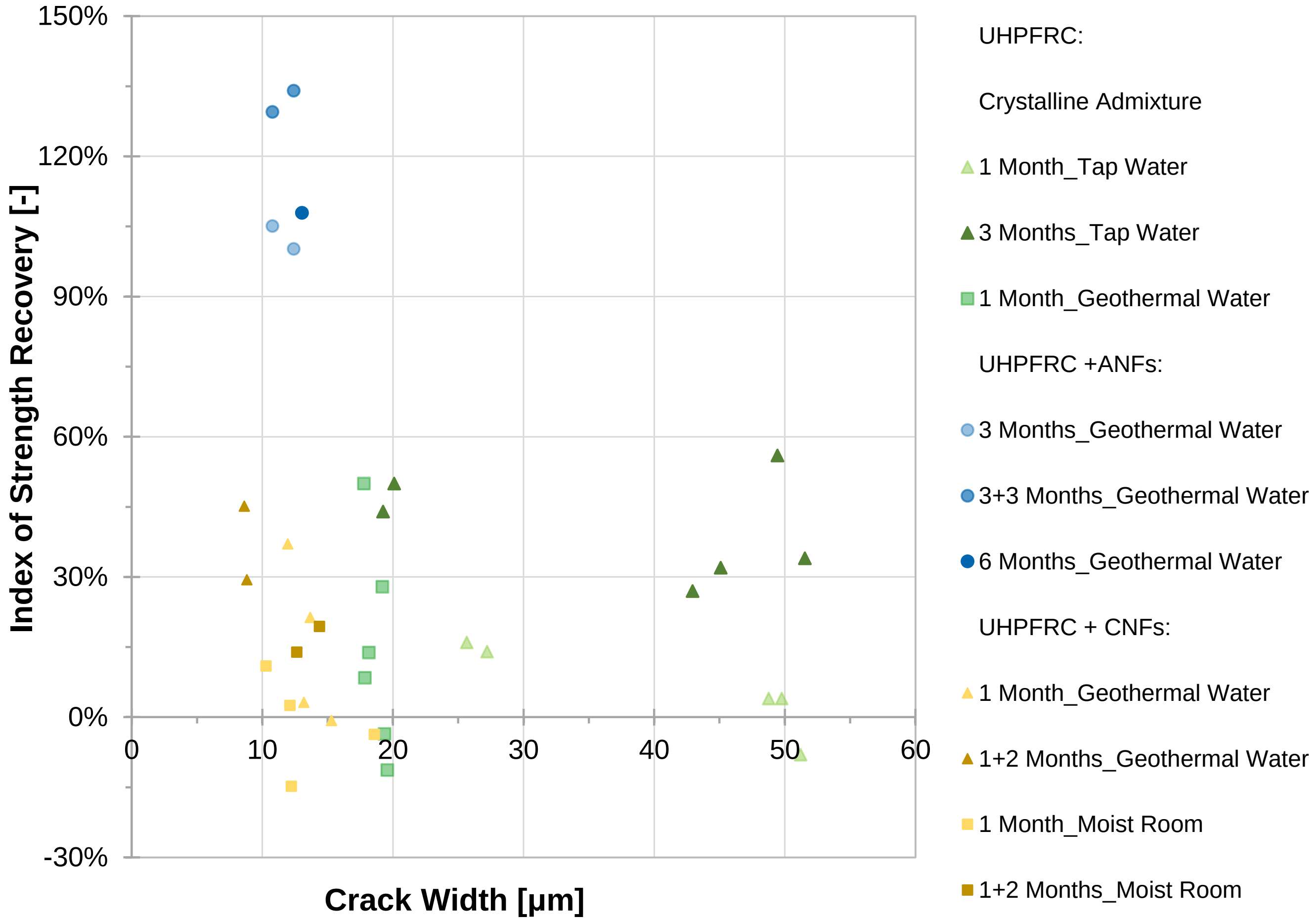

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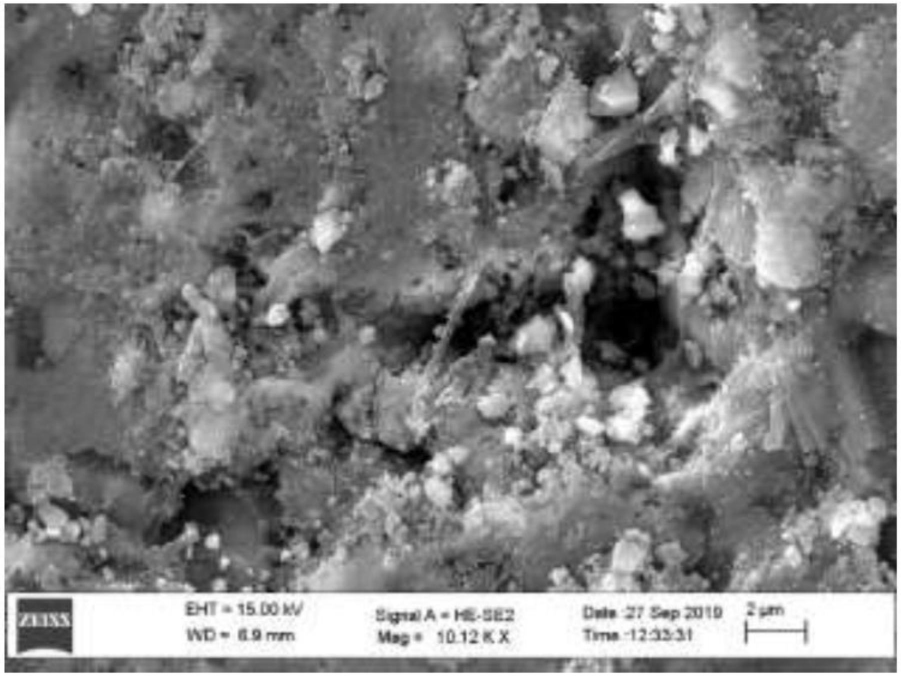
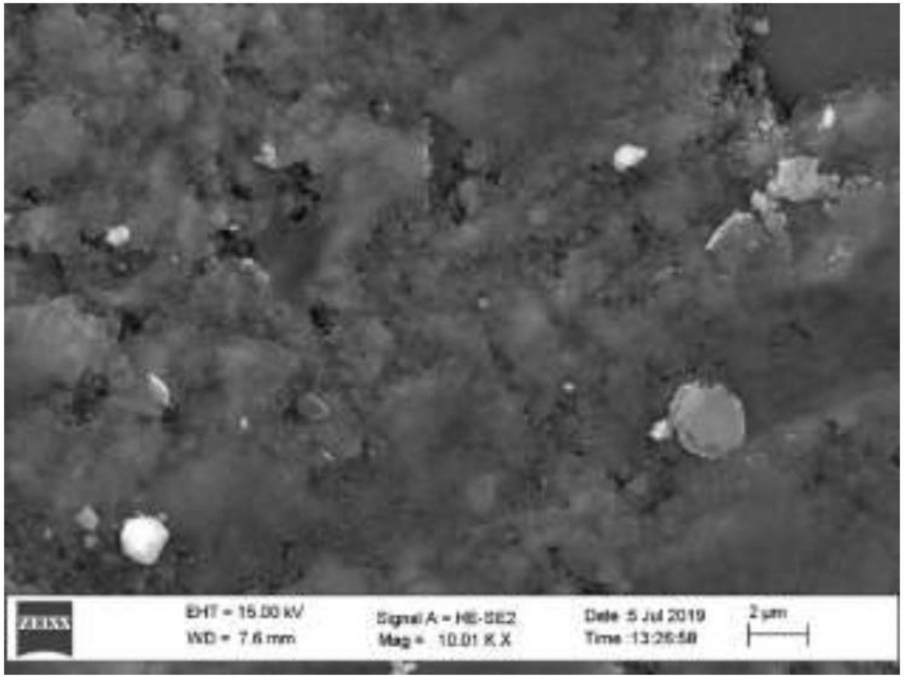
The ReSHEALience project strategy: towards a novel holistic design approach

With/without alumina nanofibres – curing in moist room

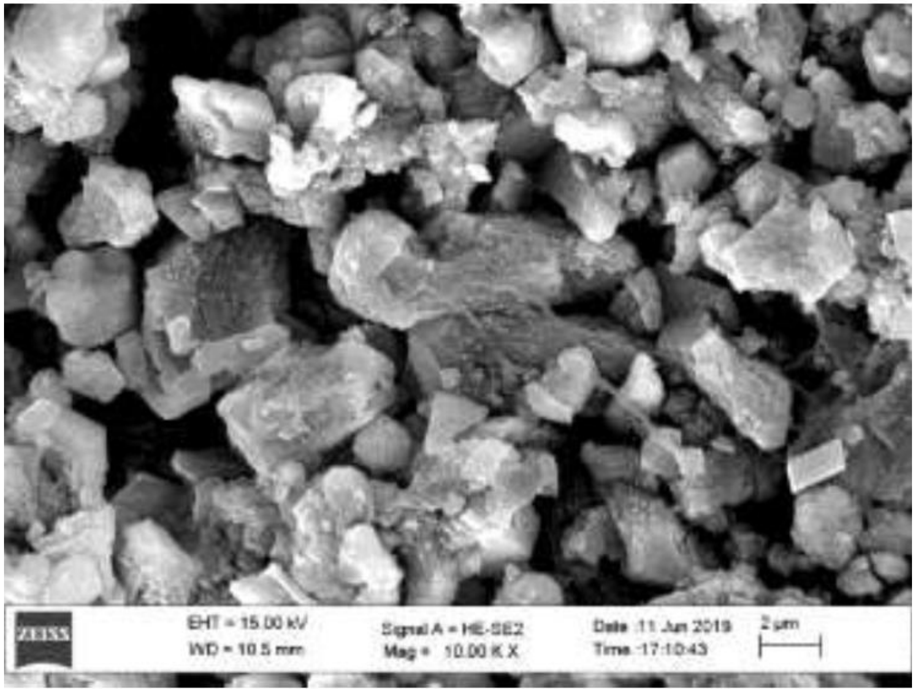


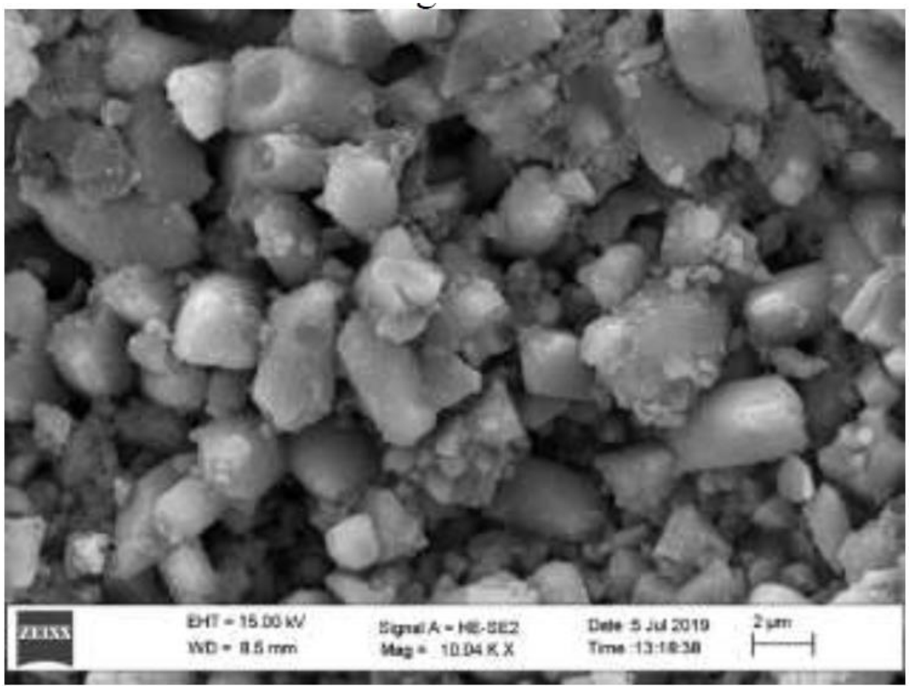


Cuenca et al., CCC 2022

The ReSHEALience project strategy: towards a novel holistic design approach

With/without alumina nanofibres – curing in geothermal water

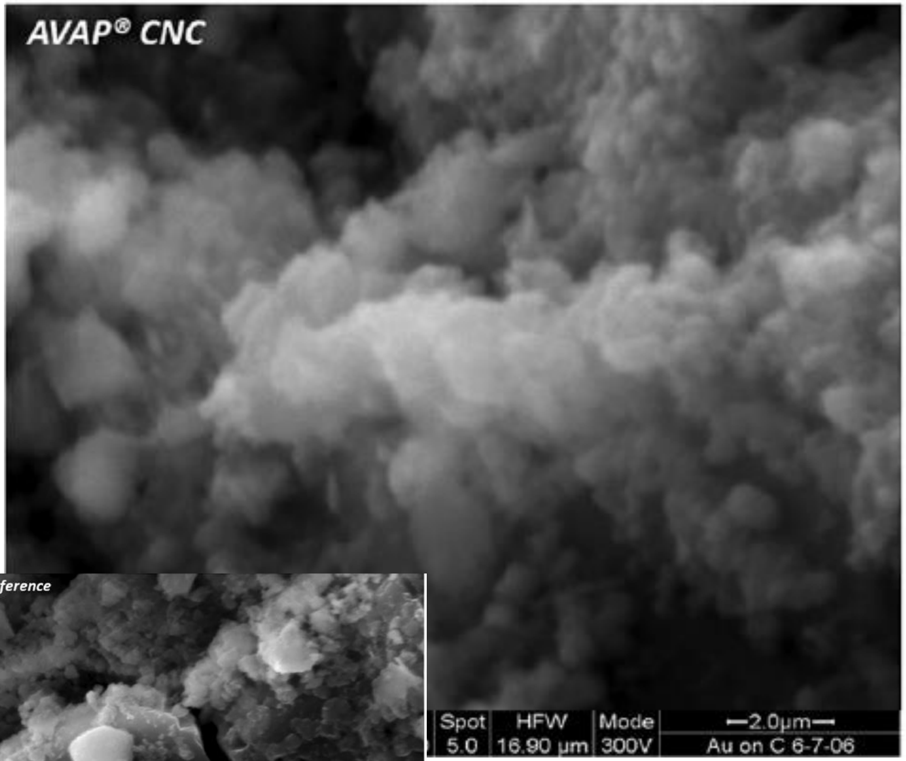


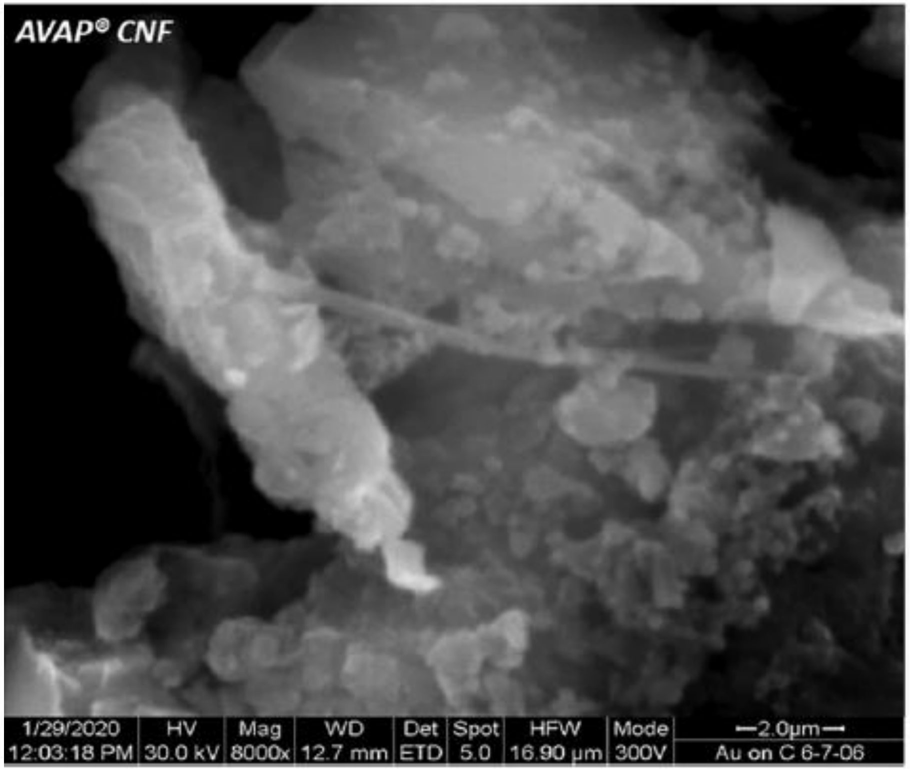


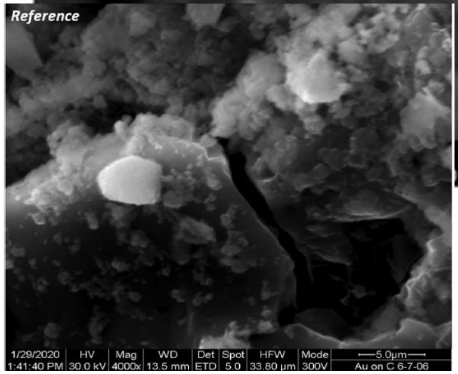
Cuenca et al., CCC 2022

The ReSHEALience project strategy: towards a novel holistic design approach

With/without cellulose nanofibrils/crystals – curing in moist room



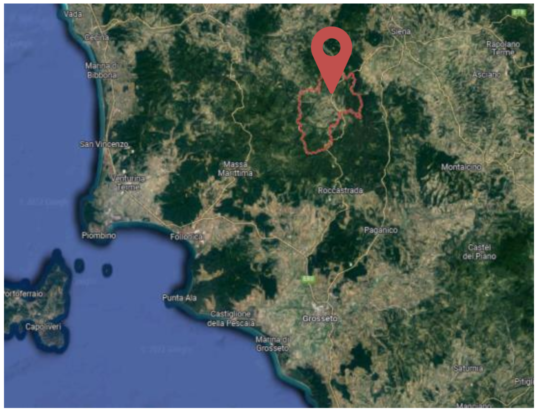




Deze et al., Materials Today 2022

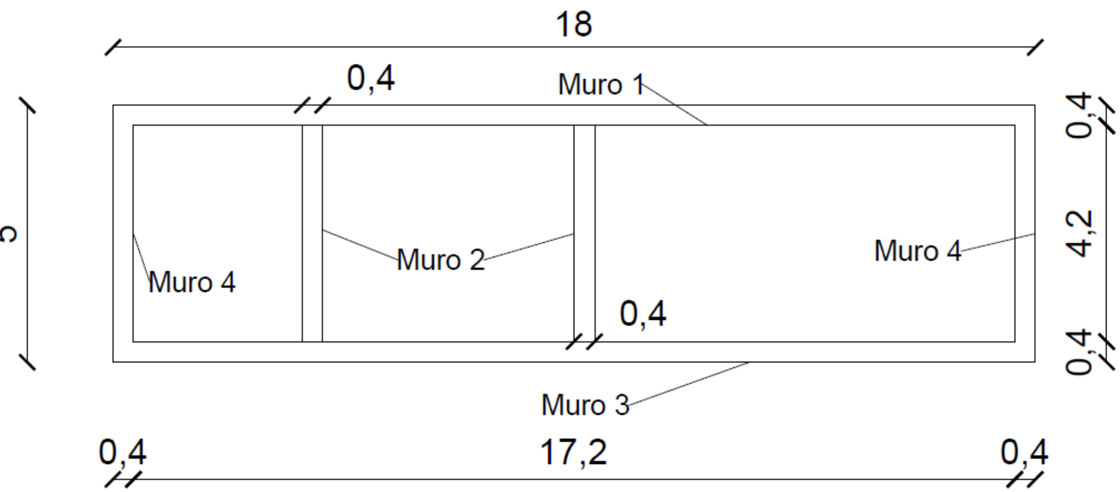
The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

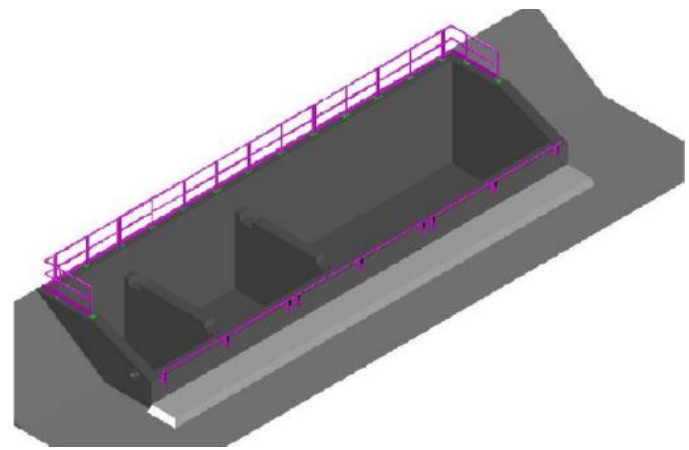
A real case study



Chiusdino (SI) (Italy)

Enel Green Power





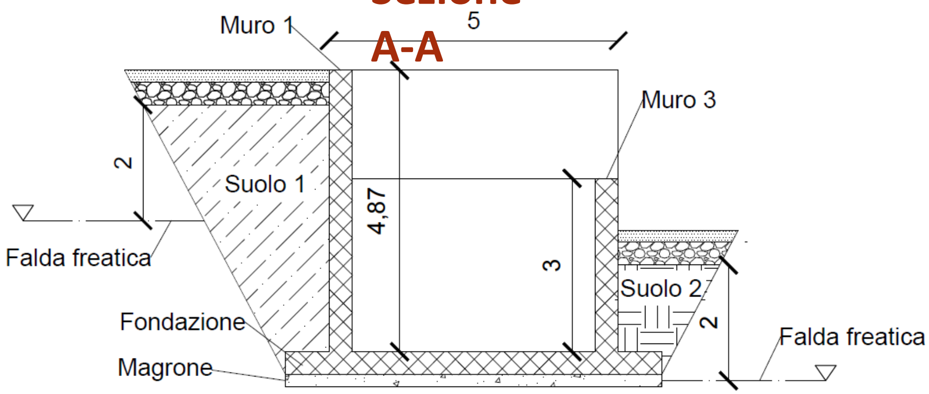
Al-Obaidi et al., CSCM, 2022

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

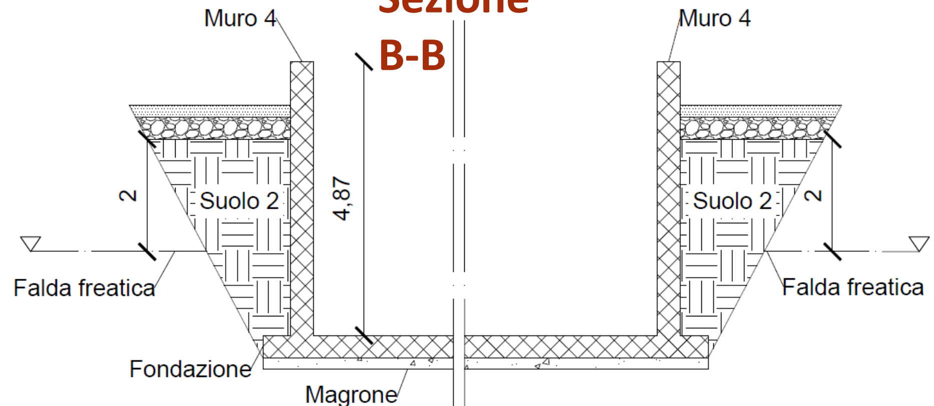
A real case study

Al-Obaidi et al., CSCM, 2022

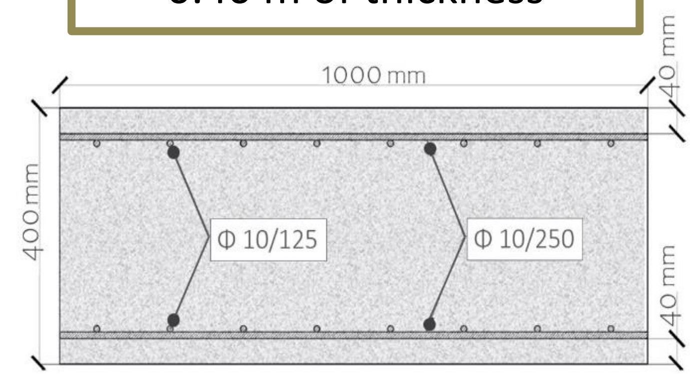
Sezione A-A



Sezione B-B



0.40 m of thickness



Ordinary Reinforced Concrete

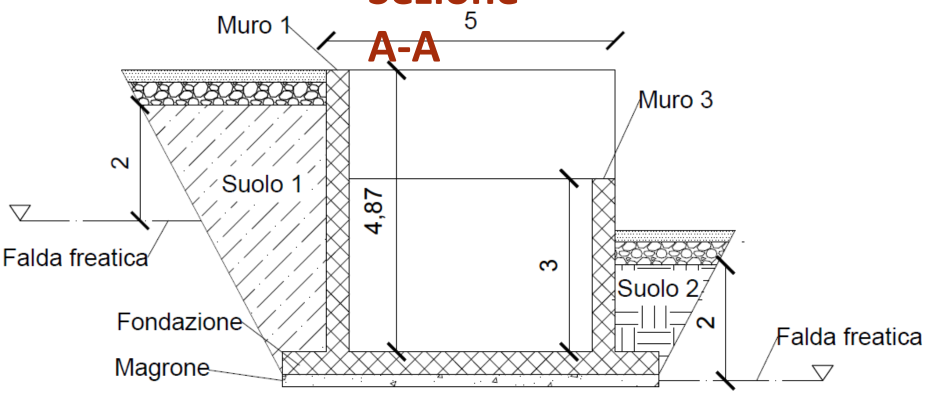
Costituents [Kg/m³]	
CEM I 42.5	350
Water	207
Gravel	960
Sand	950
Superplasticizer	3.5

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

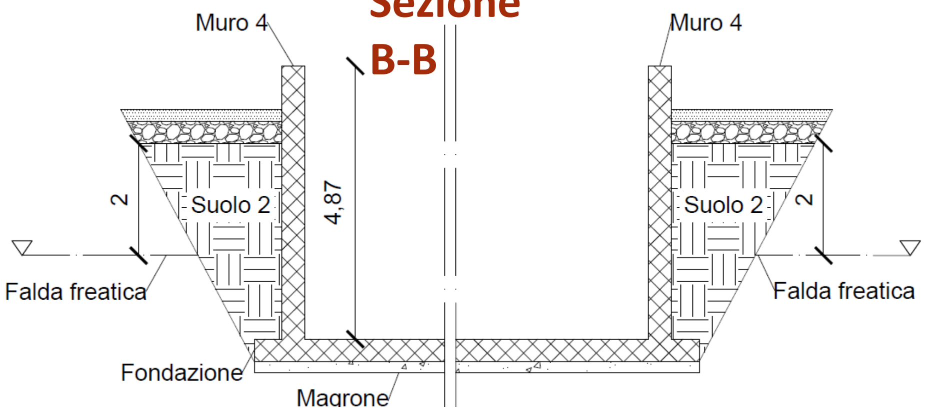
A real case study

Al-Obaidi et al., CSCM, 2022

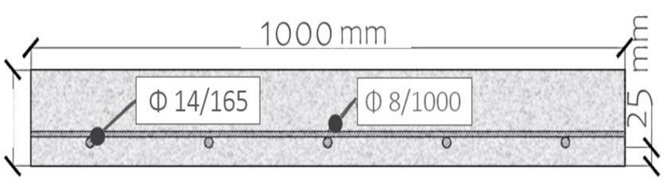
Sezione A-A



Sezione B-B



down to 0.15 m of thickness

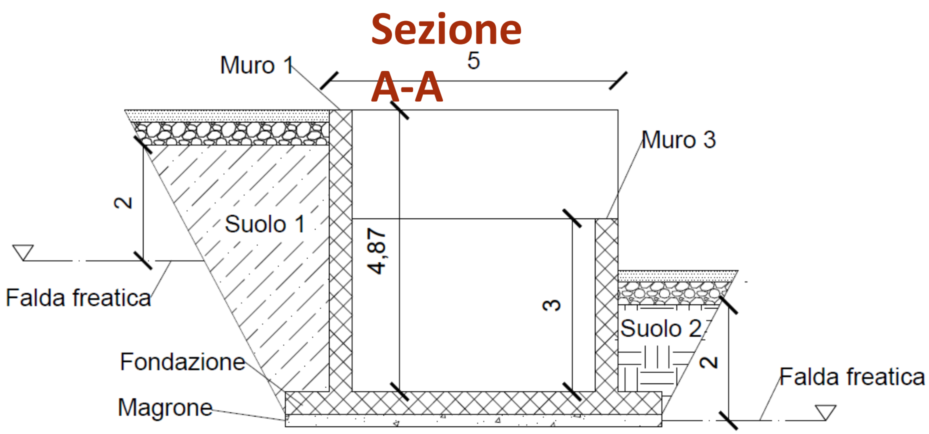


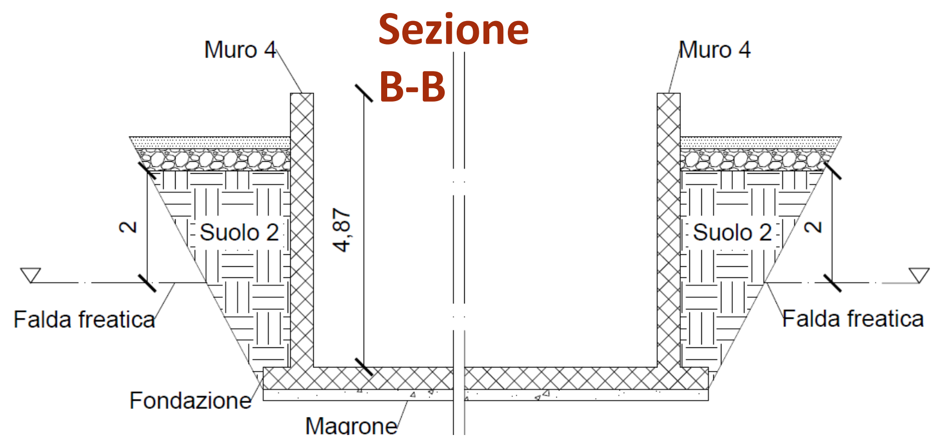
Mix-design UHPC

Costituents [Kg/m³]	
CEM I 52.5	600
GGBS	500
Water	200
Steel fibres (20/0.22)	120
Sand (0-2mm)	982
Superplasticizer	33
Crystalline admixture	4,8

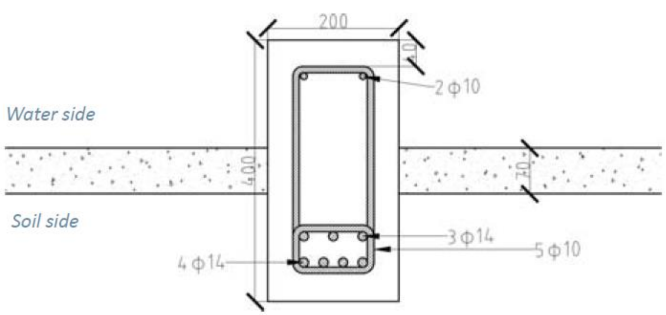
A real case study

Al-Obaidi et al., CSCM, 2022





down to 0.10 m of thickness



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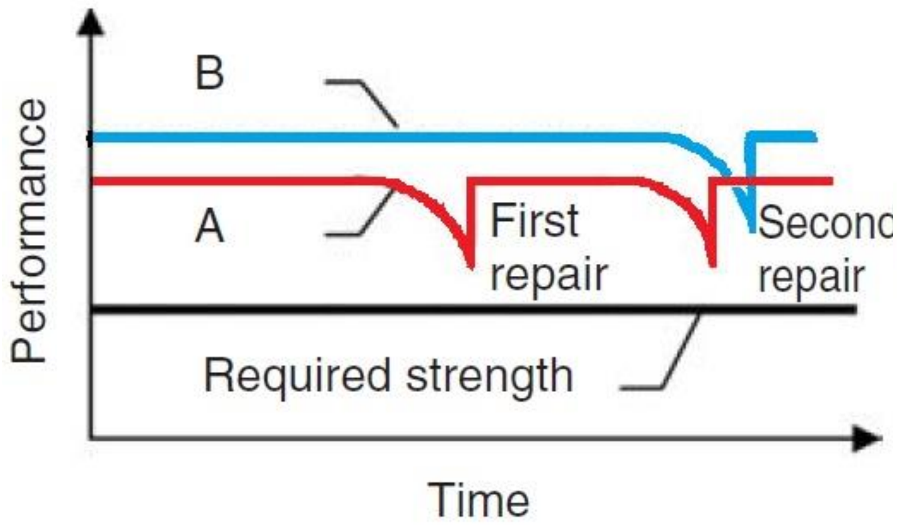
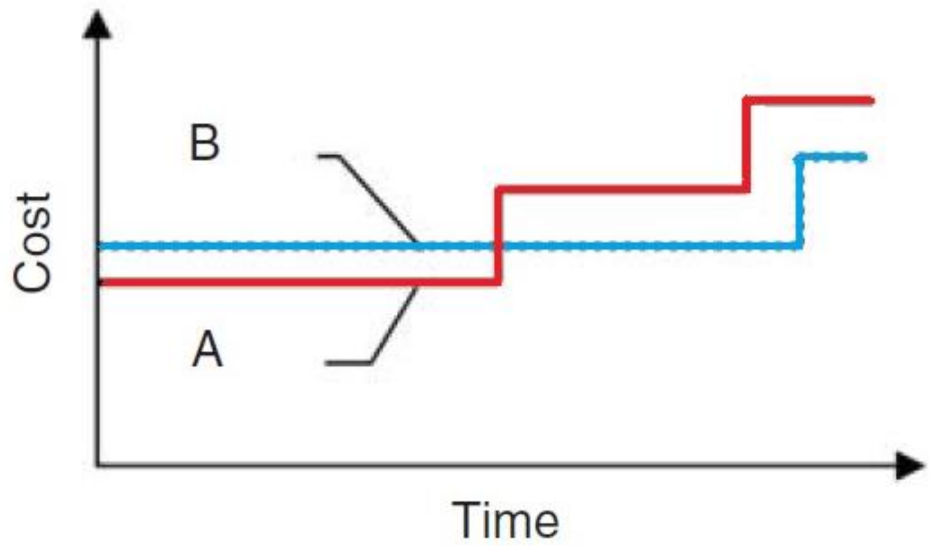
The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Ultra High Performance Concrete: *"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 under extremely aggressive exposure conditions".*

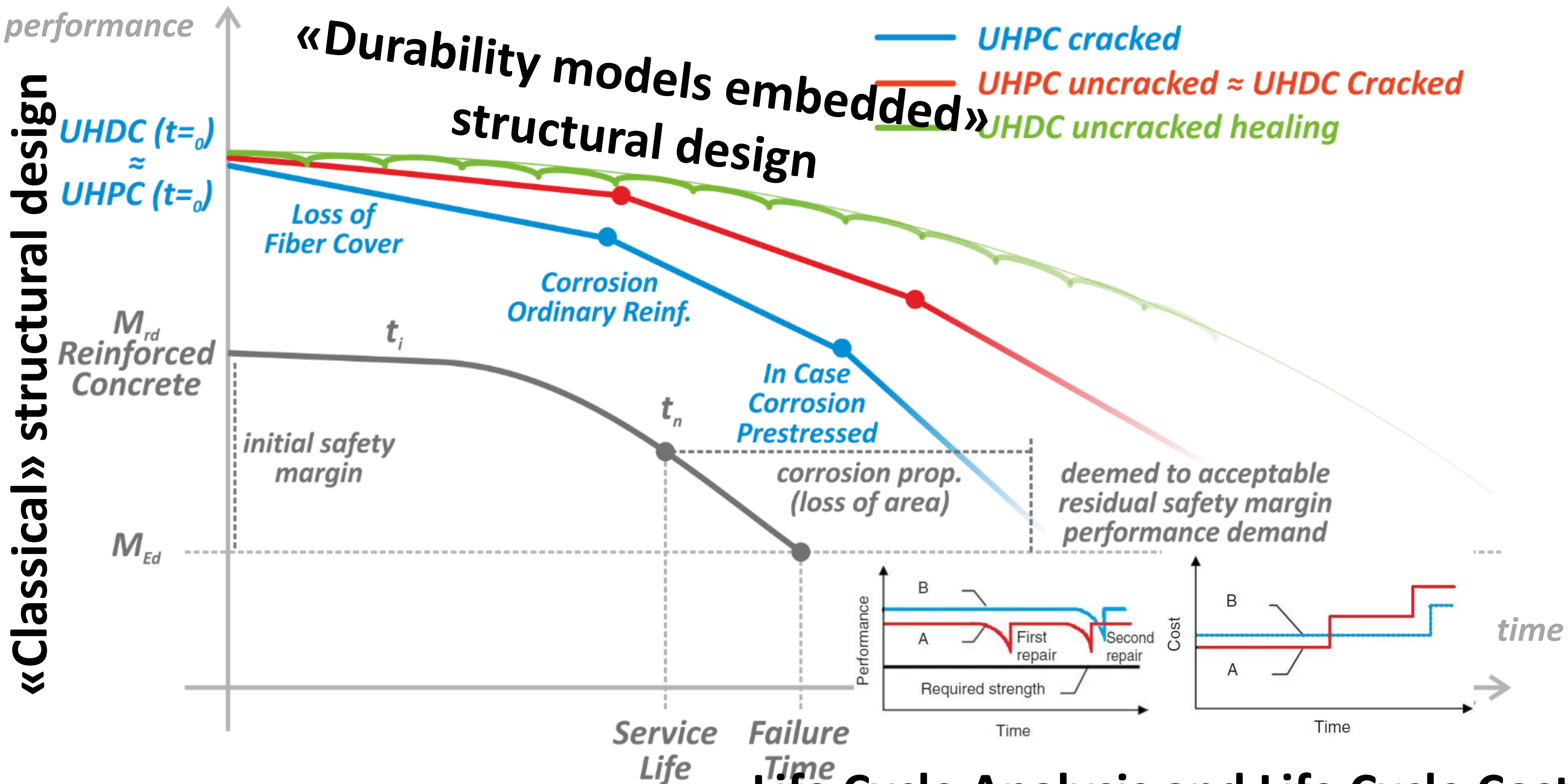




The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

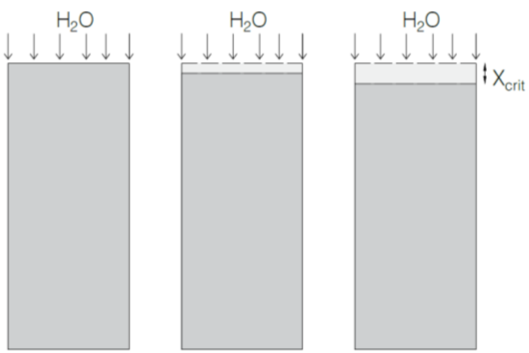
«Durability models embedded» structural design

«Classical» structural design



Life Cycle Analysis and Life Cycle Cost

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach



Chloride induced corrosion

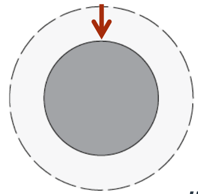
Initiation time

Propagation time

2° Fick's law

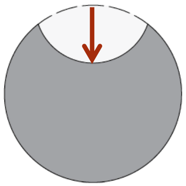
$$x_{crit} = 2\sqrt{3(t-t_0)\cdot D_{app}}\cdot\left[1-\sqrt{\frac{(C_{crit}-C_i)}{C_s-C_i}}\right]$$

Uniform corrosion



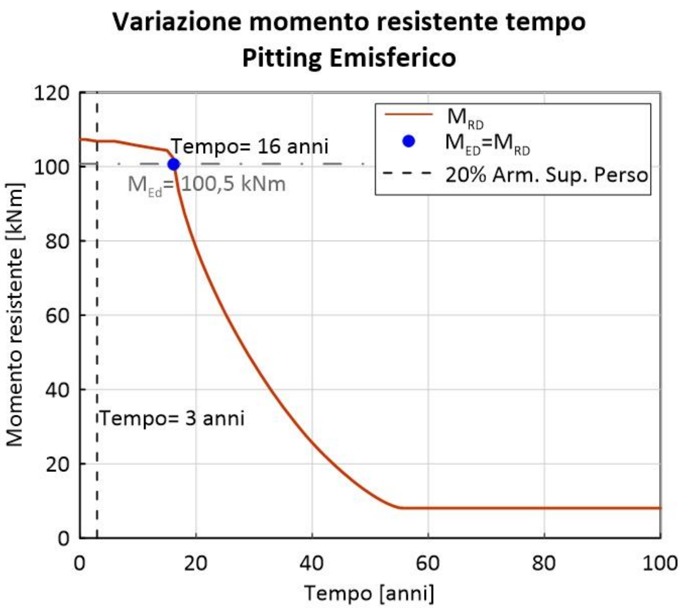
Corrosion speed: **100** $\frac{\mu m}{year}$

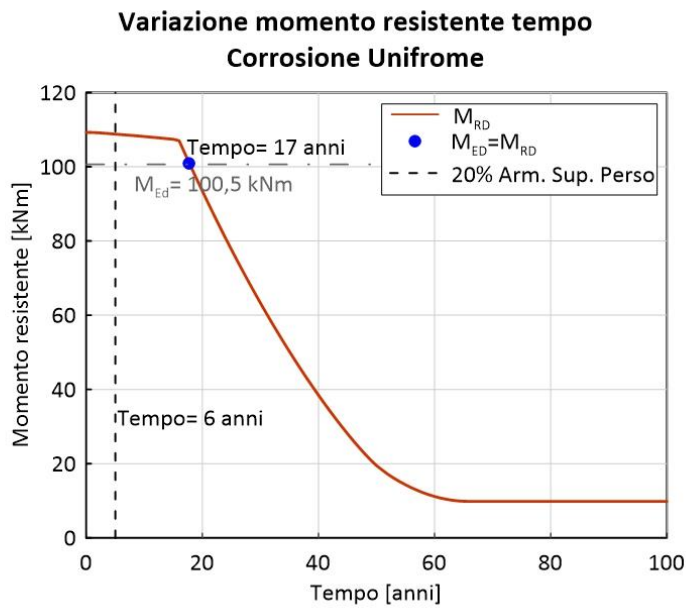
Hemispherical pit model

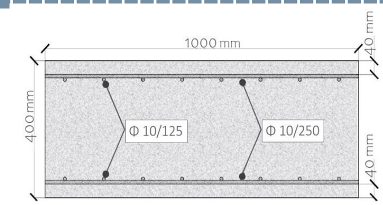


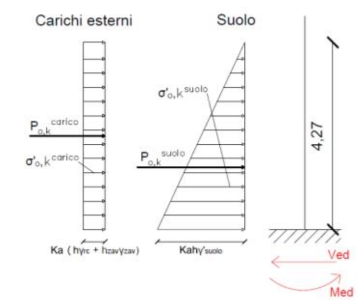
Corrosion speed: **30,54** $\frac{mm^3}{year}$

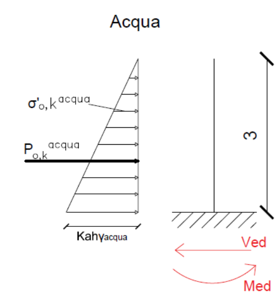
The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach











For the Ordinary Reinforced Concrete basins, it has been taken into account the **loss of 20% of the cross section of the reinforcement bars** (corresponding to internal pressure due to corrosion products expansion generating splitting tensile cracks up to 1 mm opening).

This occurs every 3 or 6 years depending on the type of corrosion propagation.

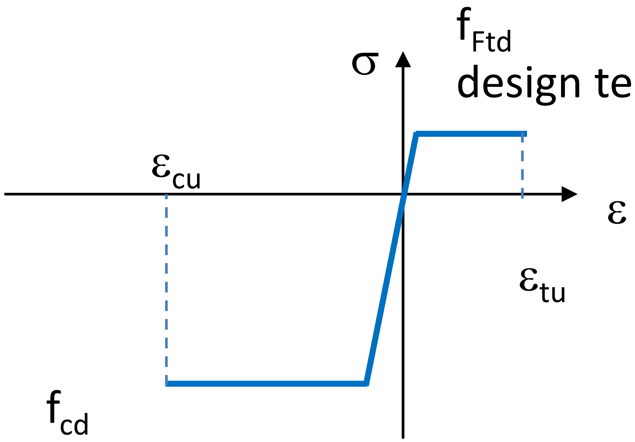
8 to 16 maintenance interventions over 50 years (3 major ones)?

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

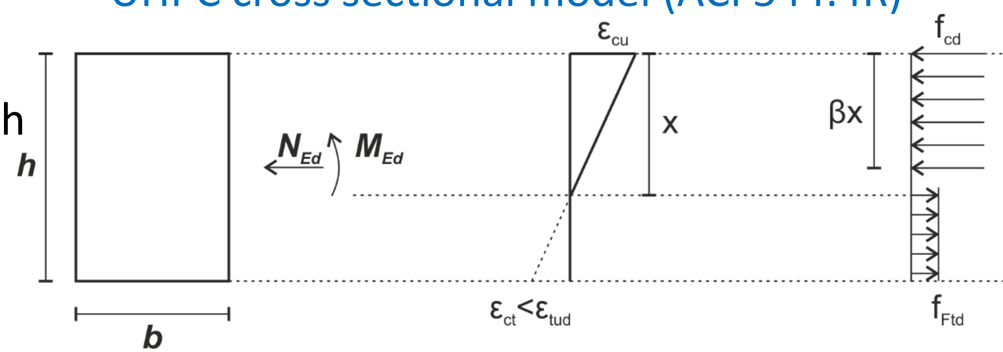
Design for durability

What direct durability indicators related to specific degradation mechanisms mean in terms of structural performance?

UHPC design constitutive model



UHPC cross sectional model (ACI 544.4R)



$$N_{Ed} = \beta \cdot b \cdot x \cdot f_{cd} - f_{Ftd} \cdot b(h-x)$$

$$M_{Rd}(t_0) = \beta \cdot b \cdot x \cdot f_{cd}\left(\frac{h}{2} - \frac{\beta}{2} \cdot x\right) + f_{Ftd} \cdot b(h-x) \cdot \left(\frac{h}{2} - \frac{h-x}{2}\right) \cong \boldsymbol{f_{Ftd} \cdot b\,\frac{h^2}{2}}$$

Al-Obaidi et al., Infrastructures, 2020

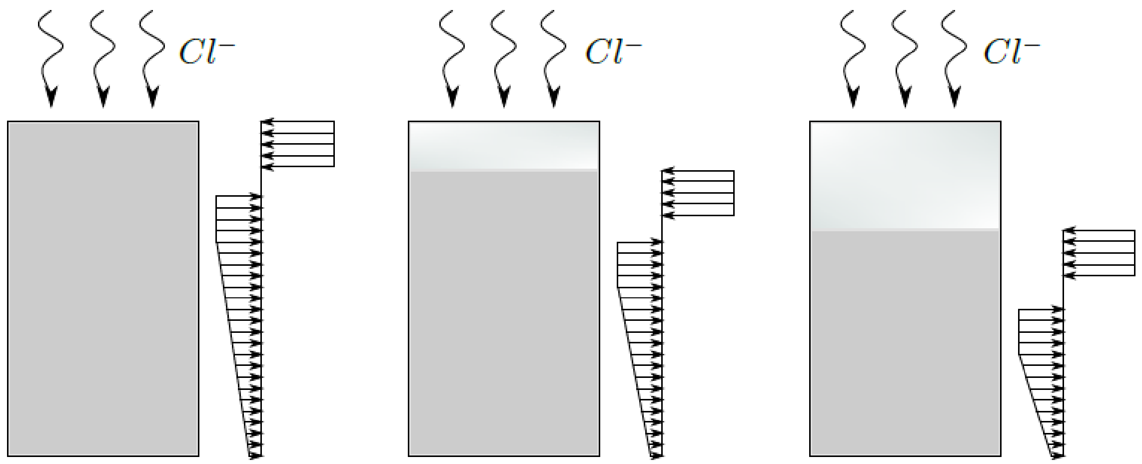
The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Design for durability

How can we «scale up» to higher level approaches?

What direct durability indicators related to specific degradation mechanisms mean in terms of structural performance?

How do we evaluate $M_{Rd}(t)$? – chloride/sulphate attack



Al-Obaidi et al., Infrastructures, 2020

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Design for durability

What direct durability indicators related to specific degradation mechanisms mean in terms of structural performance?

How do we evaluate $M_{Rd}(t)$? – chloride/sulphate attack

$$M_{Rd}(t) = f_{Ftd}\, b\, \frac{\left(h - xcrit(t)\right)^2}{2}$$

$$x_{crit} = 2\sqrt{3(t - t_0) \cdot D_{app}} \cdot \left[1 - \sqrt{\frac{(C_{crit} - C_i)}{C_s - C_i}}\right]$$

$$M_{Rd}(t) = f_{Ftd}\, b\, \frac{\left(h - x(t)\right)^2}{2} = f_{Ftd}\, b\, \frac{\left(60 - a\sqrt{t}\right)^2}{2}$$ leaching

$$M_{Rd}(t) = f_{Ftd}\, b\, \frac{\left(h - x(t)\right)^2}{2} = f_{Ftd}\, b\, \frac{(60 - k_e t)^2}{2}$$ erosion

Al-Obaidi et al., Infrastructures, 2020

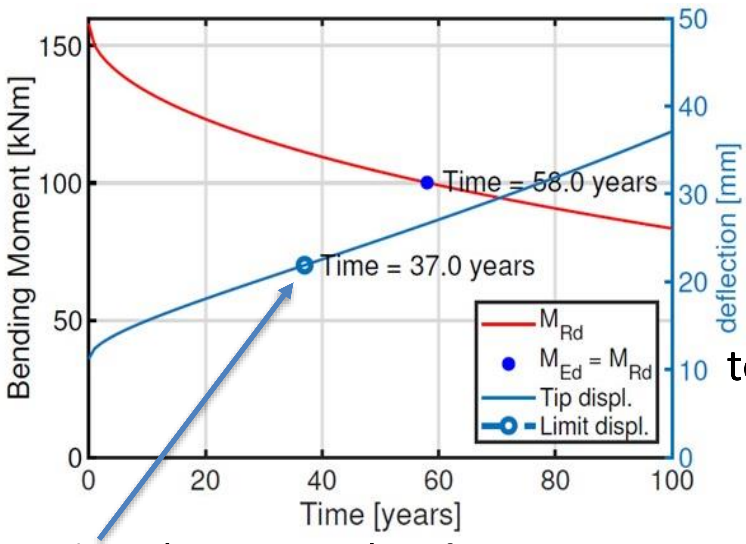
The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Design for durability

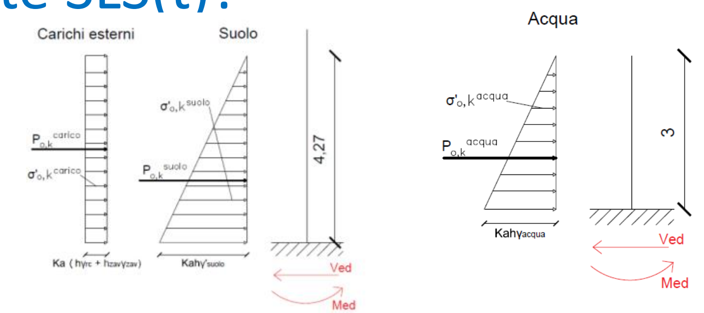
What direct durability indicators related to specific degradation mechanisms mean in terms of structural performance?

How do we evaluate $M_{Rd}(t)$? – chloride/sulphate attack

How do we evaluate SLS(t)?



1 maintenance in 50 years



Shift from ULS governed design
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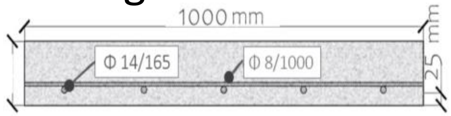

di Summa et al., Structural Concrete 2023, submitted

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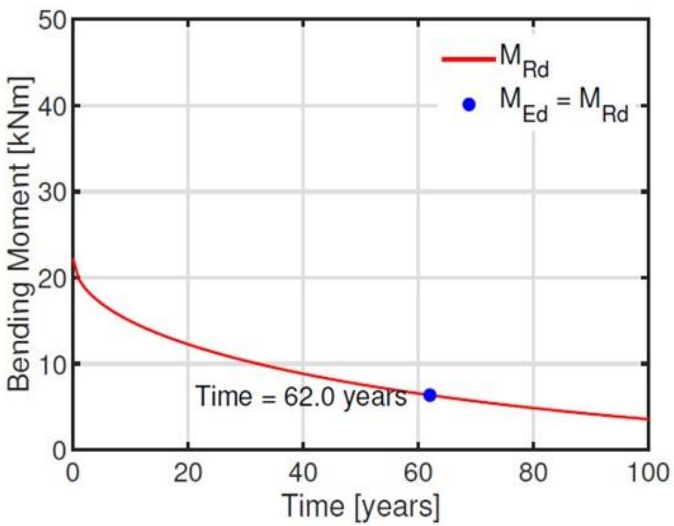
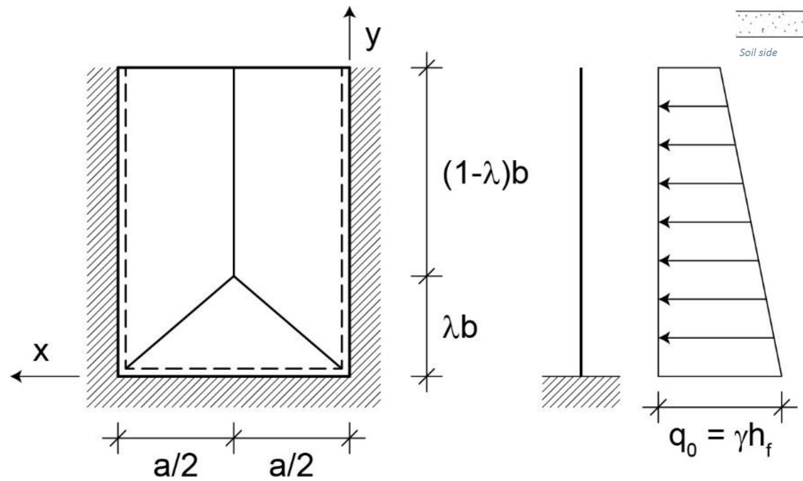
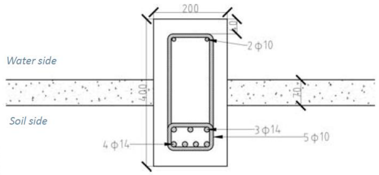






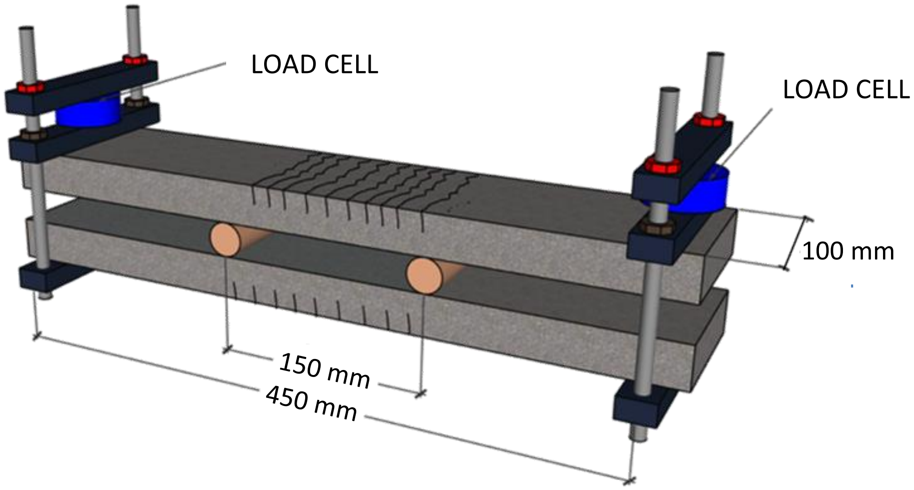
no maintenance in 50 years

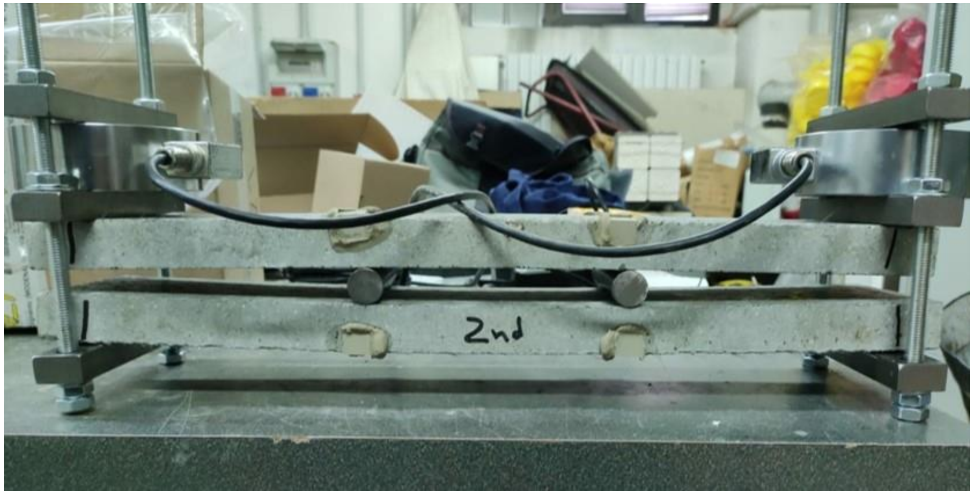
di Summa et al., Structural Concrete 2023, submitted

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Design for durability

Identify the real «in structure» material behaviour





Davolio et al., CCC 2023

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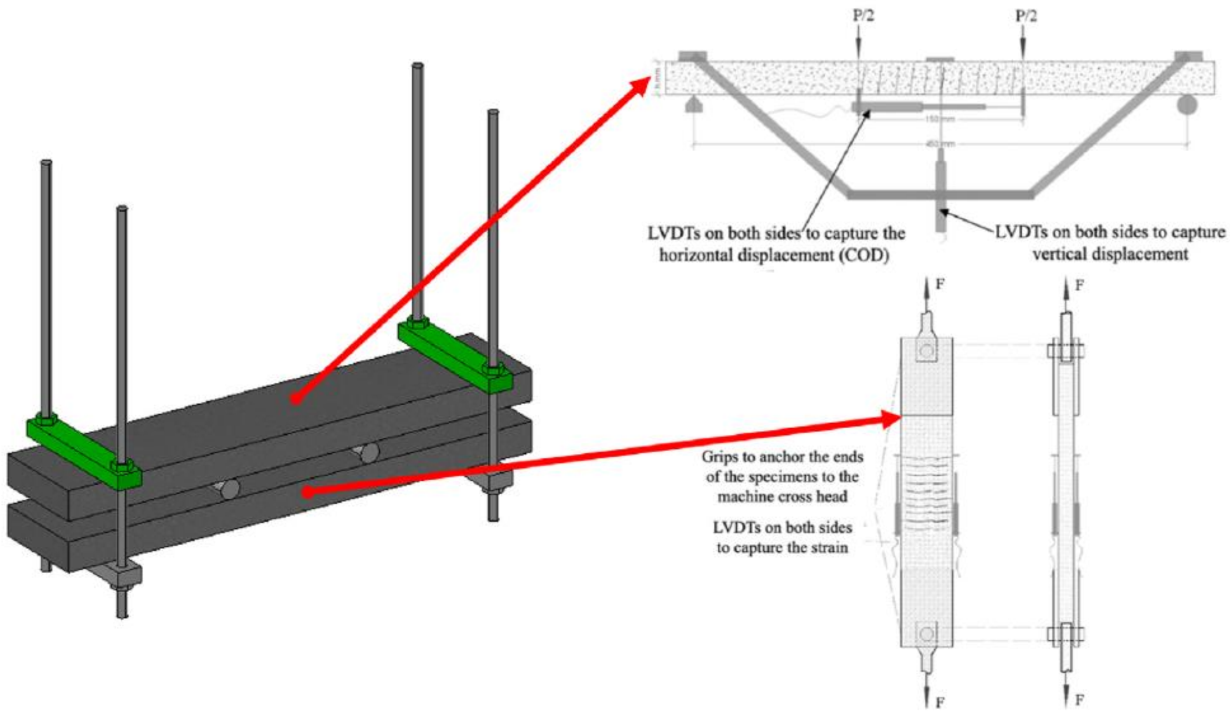

Davolio et al., CCC 2023

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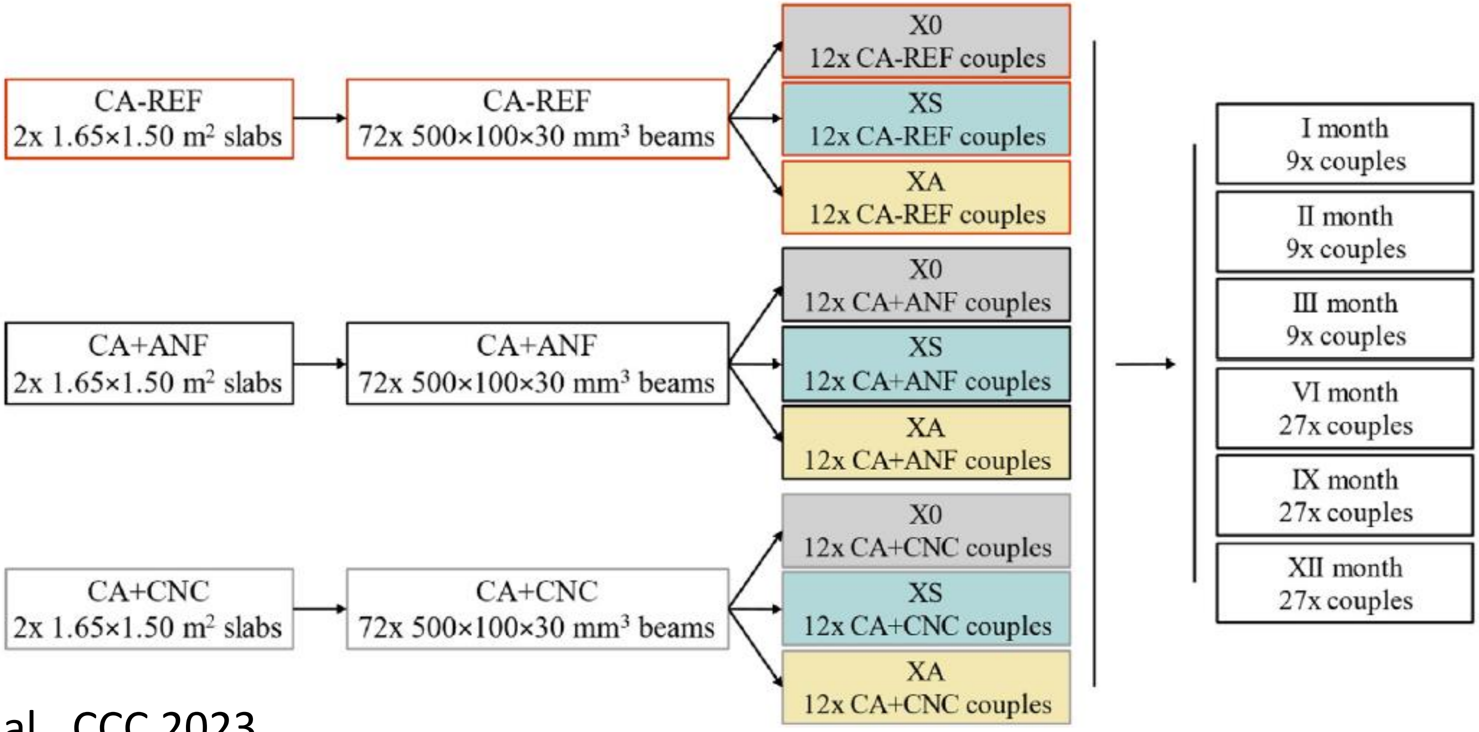

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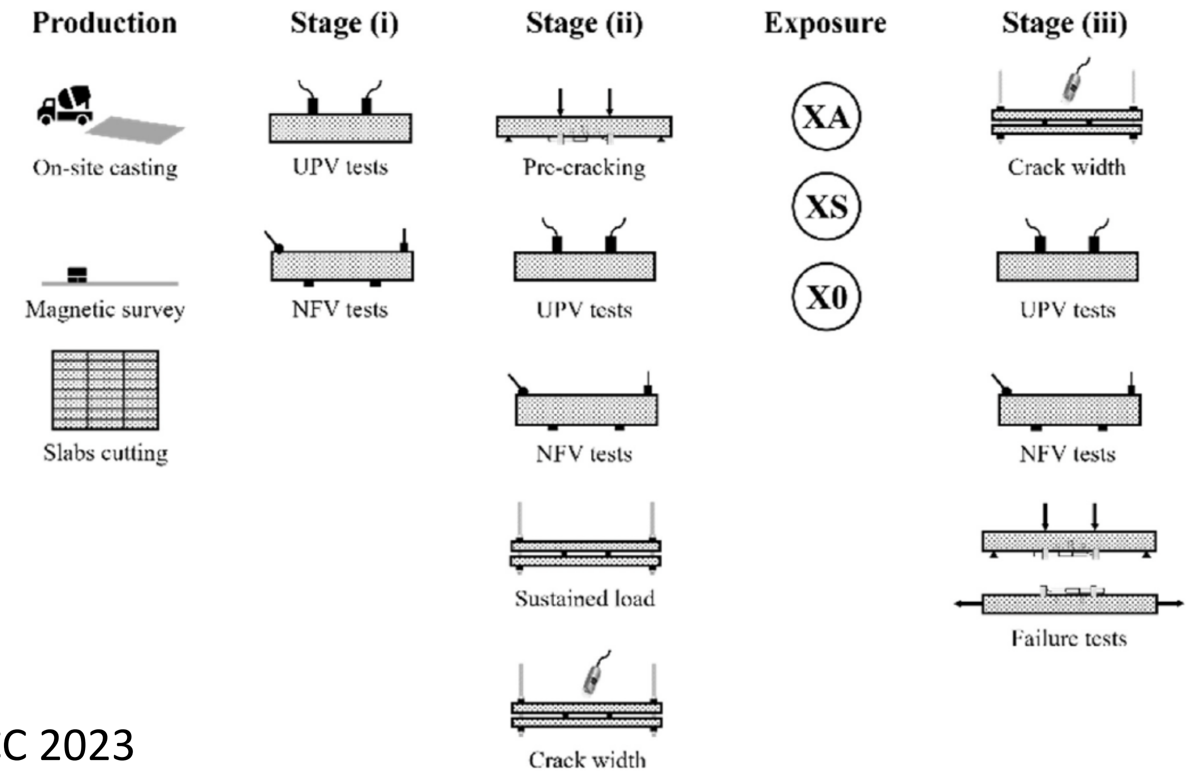

Davolio et al., CCC 2023

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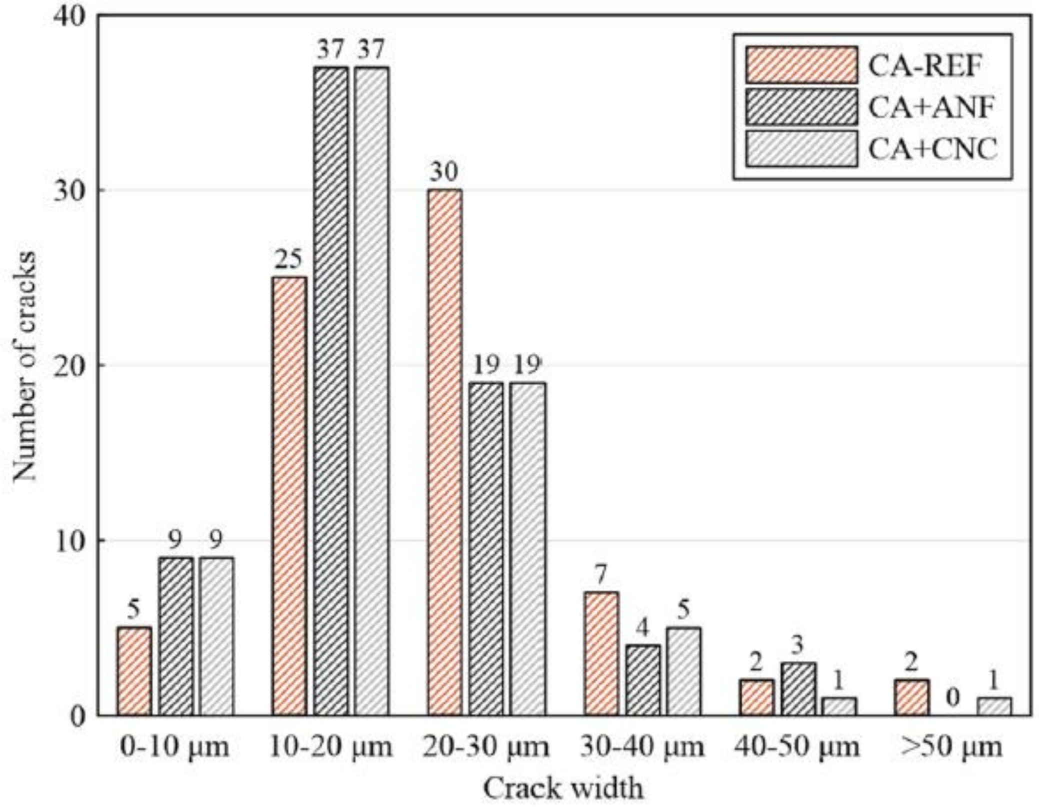

Davolio et al., CCC 2023

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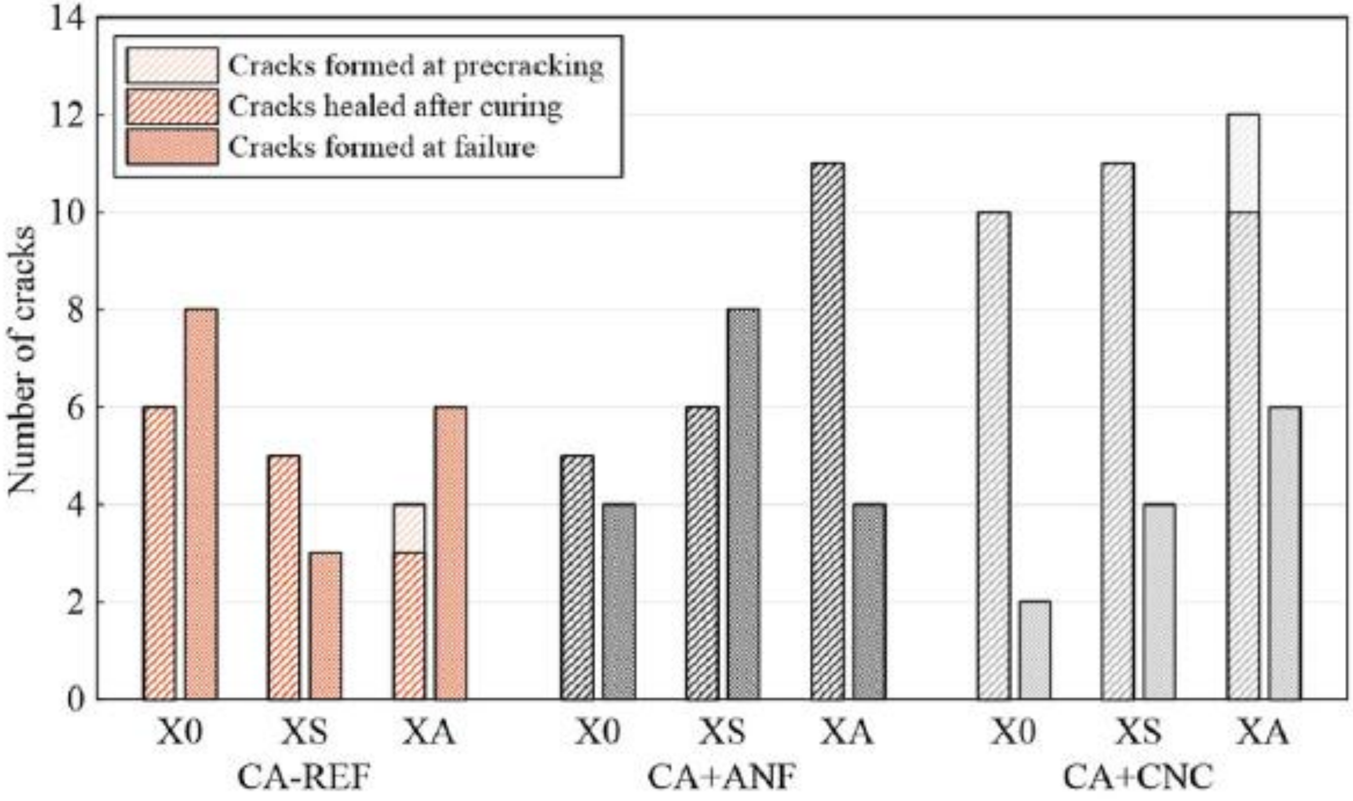

Davolio et al., CCC 2023

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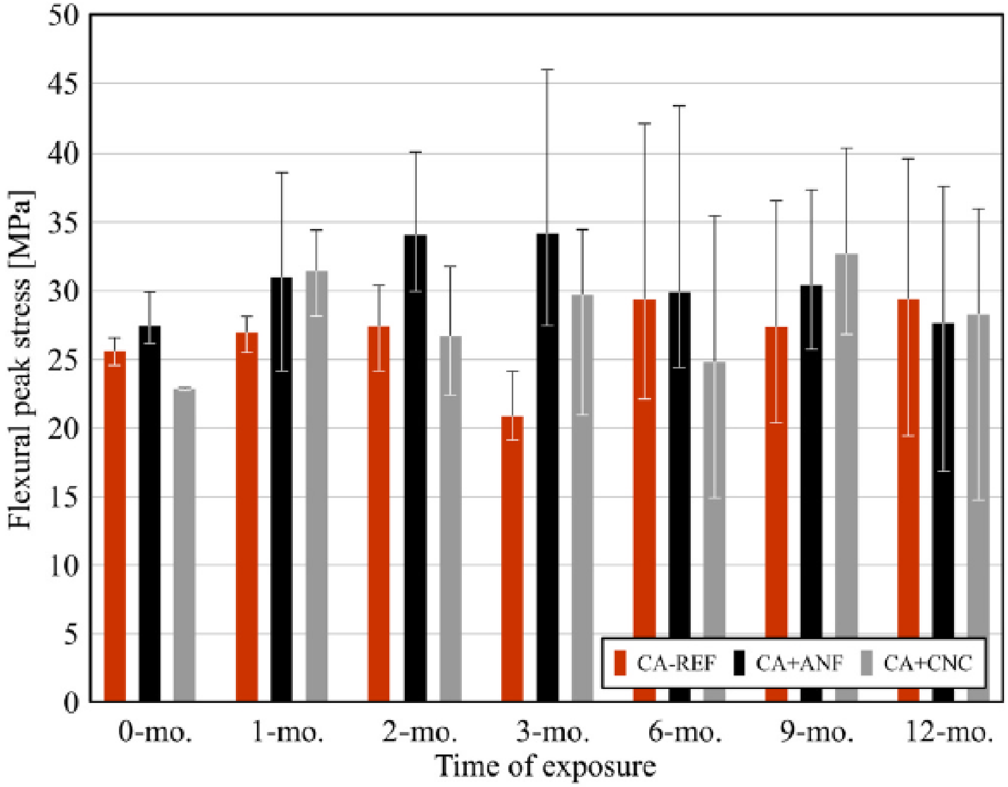
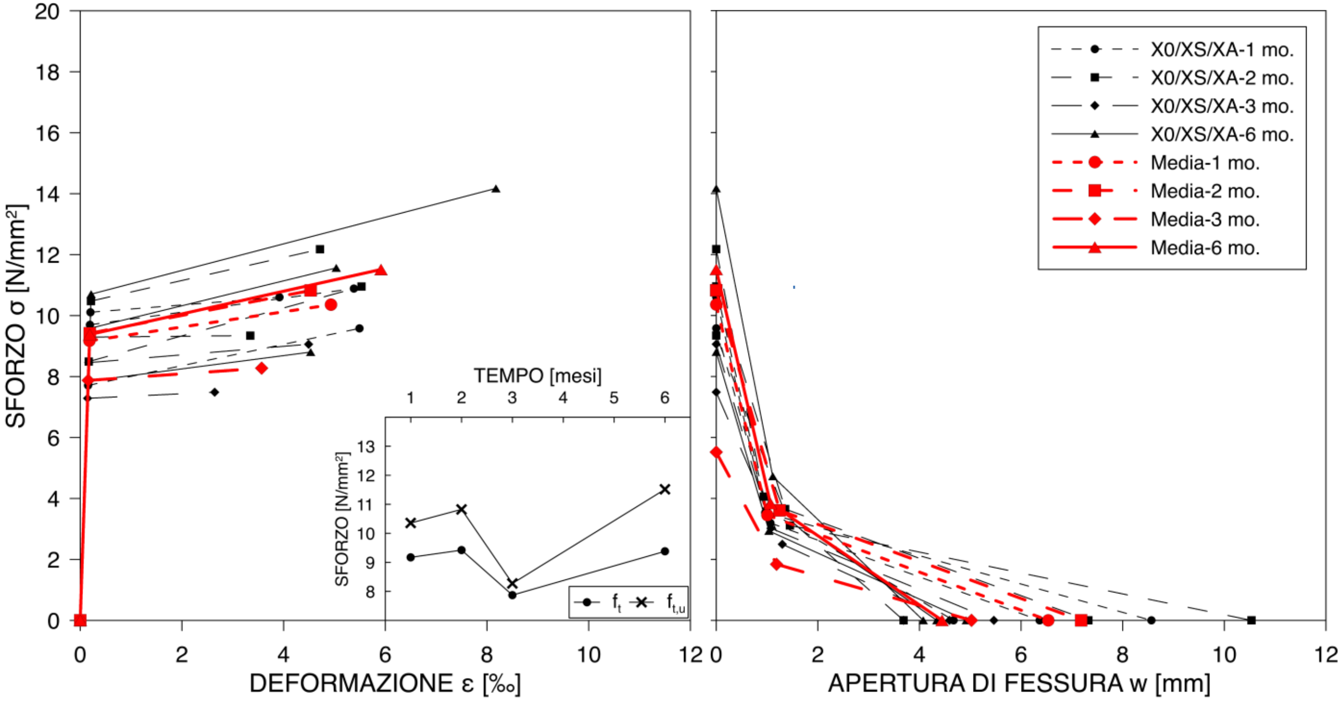


Davolio et al., CCC 2023

The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Design for durability

How do we evaluate $M_{Rd}(t)$? – evolution of material constitutive response under sustained loading in aggressive scenarios

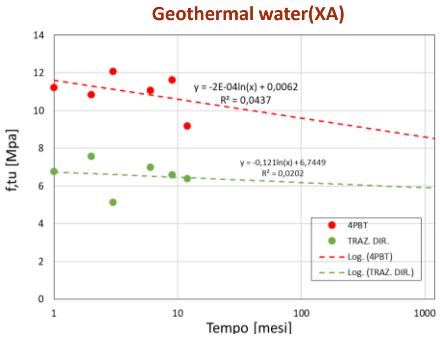


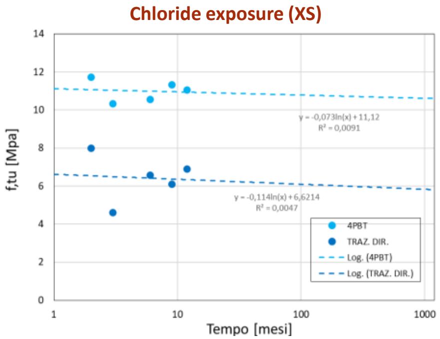
Davolio et al, 2023 CCC

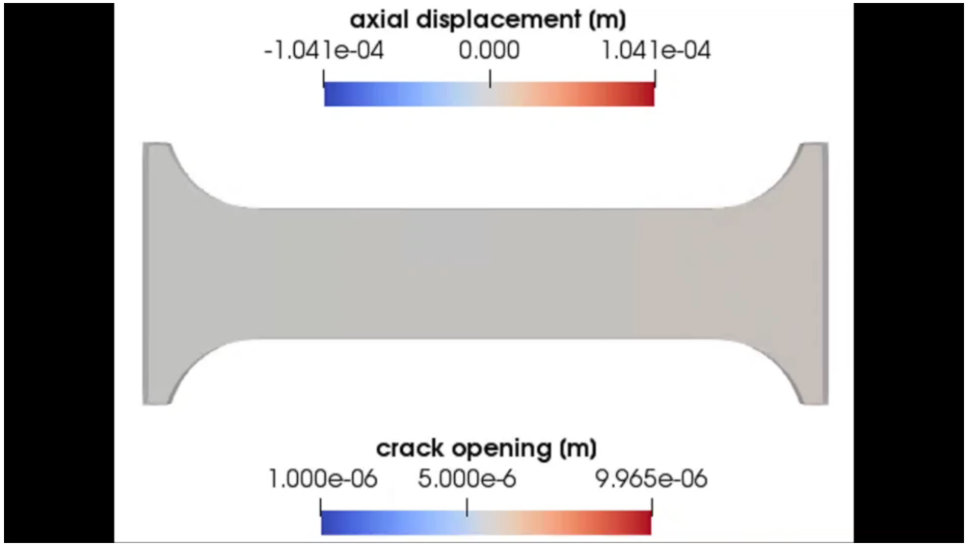
The ReSHEALience/SMARTINCs strategy: towards a novel holistic design approach

Design for durability

Evolution of material constitutive response under sustained loading in aggressive scenarios: extrapolation through numerical modelling







Davolio et al, 2023 CCC

Cibelli et al., ASCE JEngMech 2023, submitted

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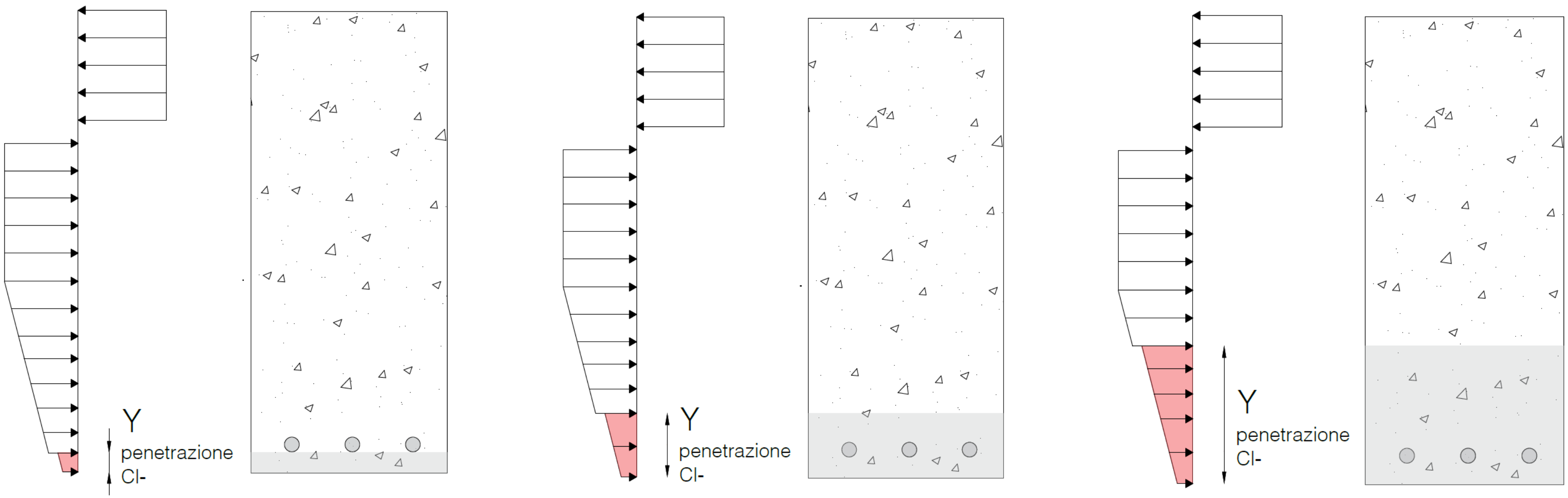

Soave et al., in preparation

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Design for durability

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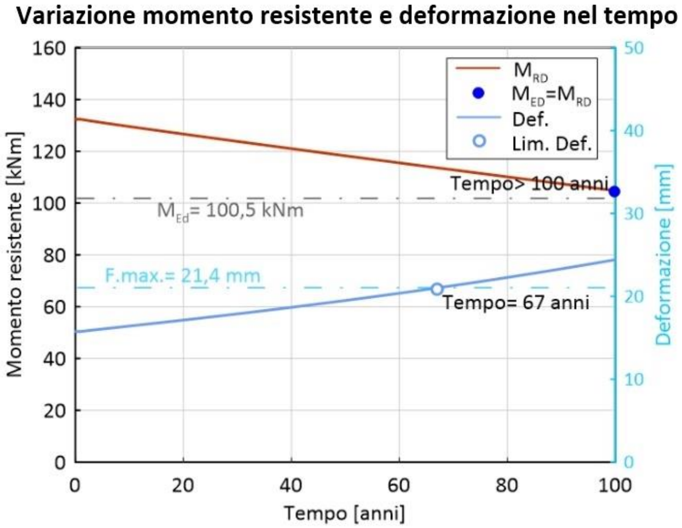

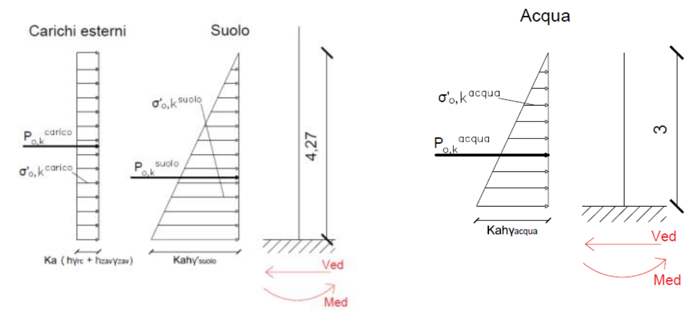

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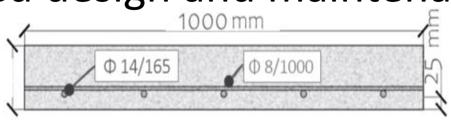

no maintenance in 50 years?

Soave et al., 2023, in preparation

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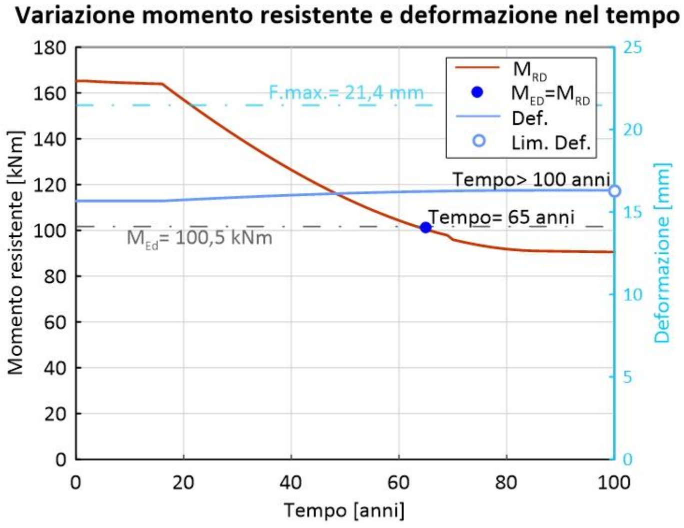

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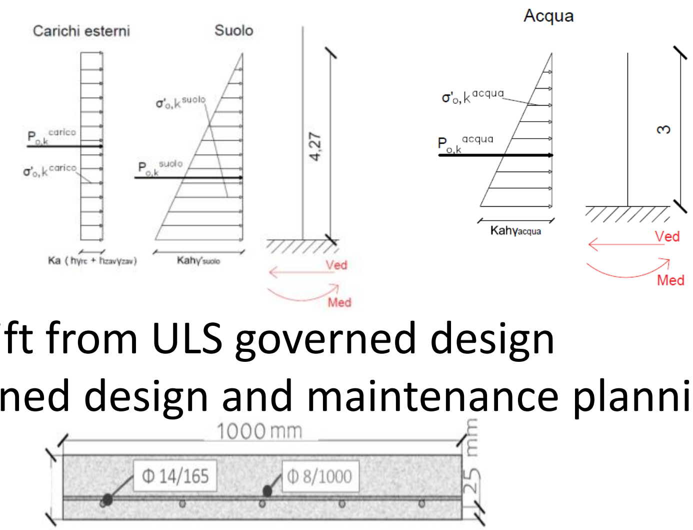

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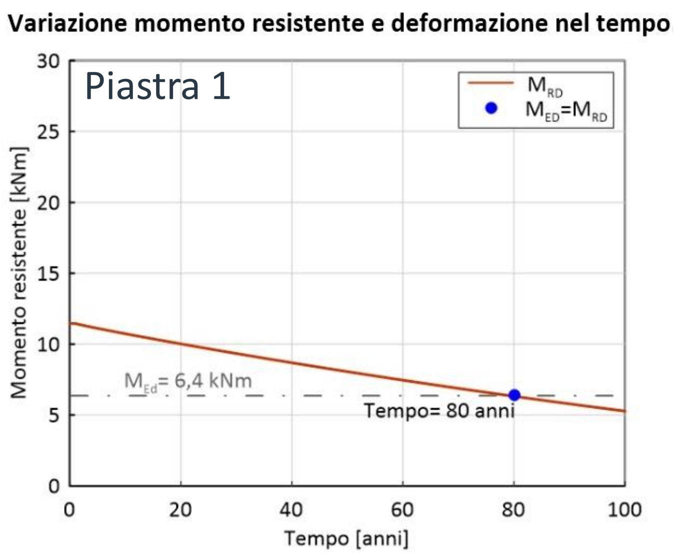

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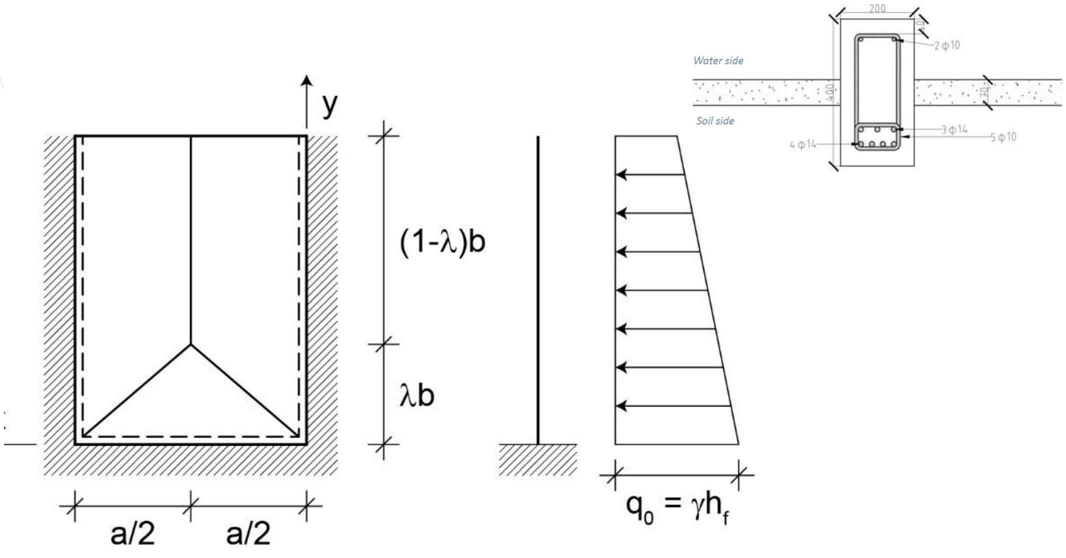

di Summa et al., Structural Concrete 2023, submitted

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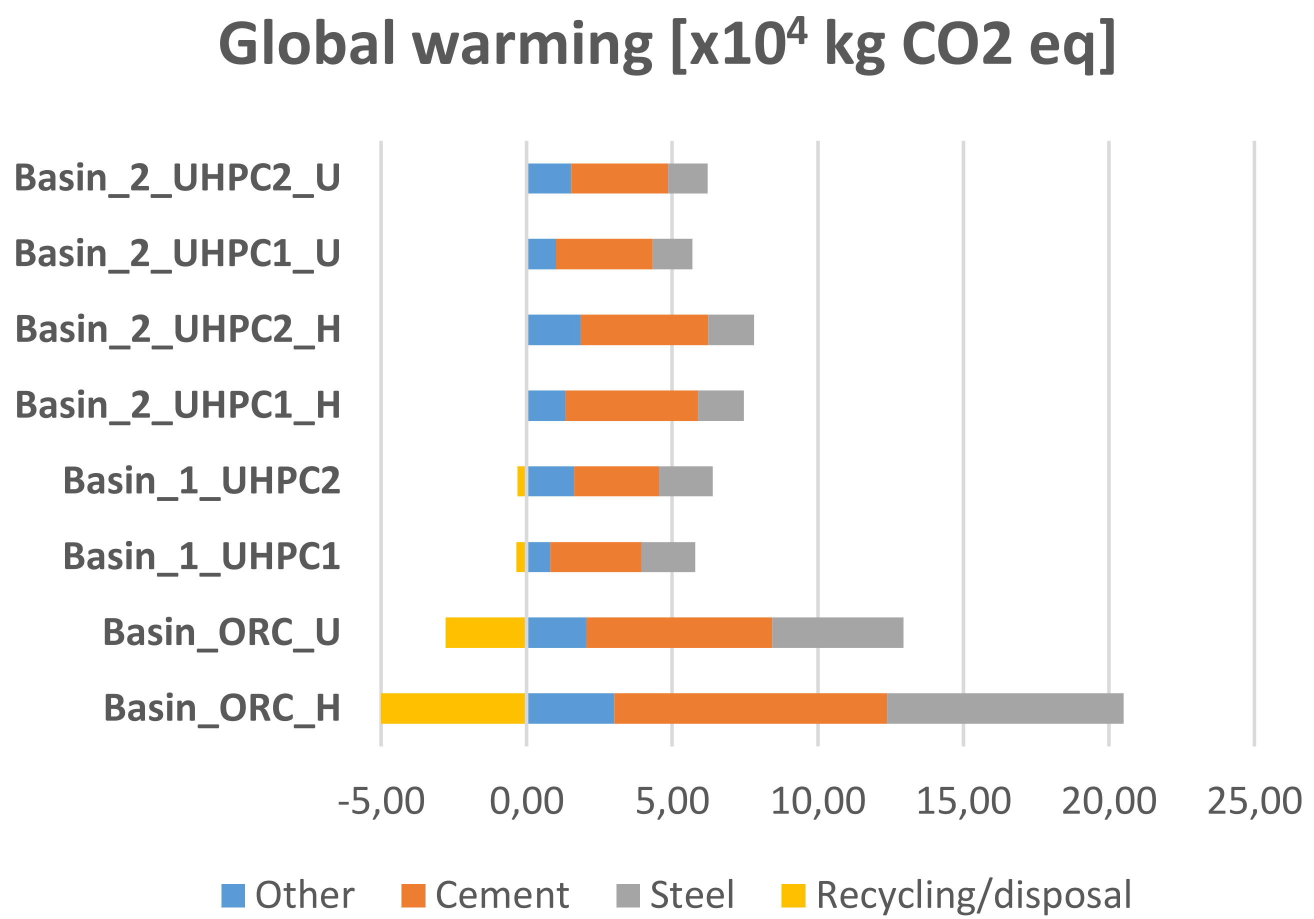

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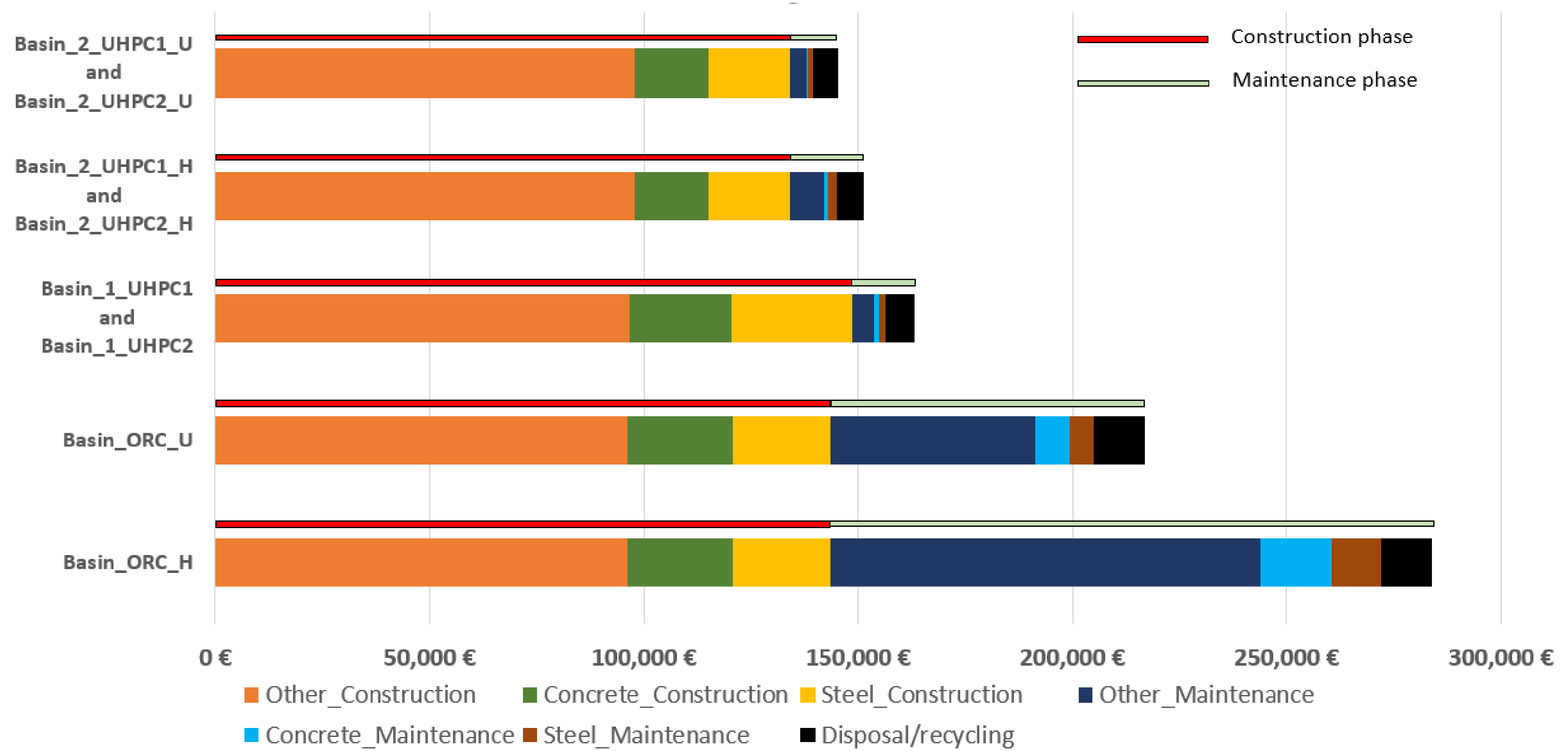

di Summa et al., Structural Concrete 2023, submitted

Concluding remarks: always advancing

Nanofunctionalized UHPC: the «material to be» to drive the green transition

Reaching **climate neutrality, circularity**, healthy food-systems and **sustainability in** agriculture, transportation, **construction**, packaging, electronic appliances, as well as completing the transition to renewable energy sources are among the greatest challenges humanity is facing today. Scientific evidence shows that action on climate change must have an interconnected and systemic response and this is exactly where advanced materials can and must deliver solutions. To achieve these solutions, Europe must **maximise the sustainability features of new advanced materials and their visibility using advanced digital technologies**. Sustainable advanced materials are a **key driver for innovation**, creating new opportunities on multiple dimensions and sectors. Our vision to enable the EU's twin green and digital transitions is anchored in **good design principles combined with synergies between advanced materials, circularity, digital and industrial technologies**.

on behalf of the ReSHEALience consortium

… and of the SMARTINCs consortium …

… and of the ReSHEALients@DICAPolimi

… and of the ReSHEALients@DICAPolimi

If you always do what you always did, you'll always get what you always got!

Thank you for your attention!

RESHEALIENCE

Ultra High Durability Concrete

PON

RICERCA E INNOVAZIONE

2014 - 2020

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani

SMARTINCS

SELF-HEALING - MULTIFUNCTIONAL - ADVANCED REPAIR TECHNOLOGIES IN CEMENTITIOUS SYSTEMS

MARIE SKLODOWSKA-CURIE ACTION

European Commission

This project receives funding from the European Union's Horizon H2020 research and innovation programme under grant agreement Nº 860006

MUSA

MULTILAYERED URBAN SUSTAINABILITY ACTION

project, funded by the European Union – NextGenerationEU, under the National Recovery and Resilience Plan (NRRP) Mission 4 Component 2 Investment Line 1.5: Strenghtening of research structures and creation of R&D "innovation ecosystems", set up of "territorial leaders in R&D"

MINRESCUE

This project receives funding from the European Union Research Fund for Coal and Steel under grant agreement Nº 899518

HINFRA™

The Large Scale Digital Concrete Extrusion Project

CEMEX

Building a better future

ENERGY VAULT

RIMOND

Liberato Ferrara, Department of Civil and Environmental Engineering

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