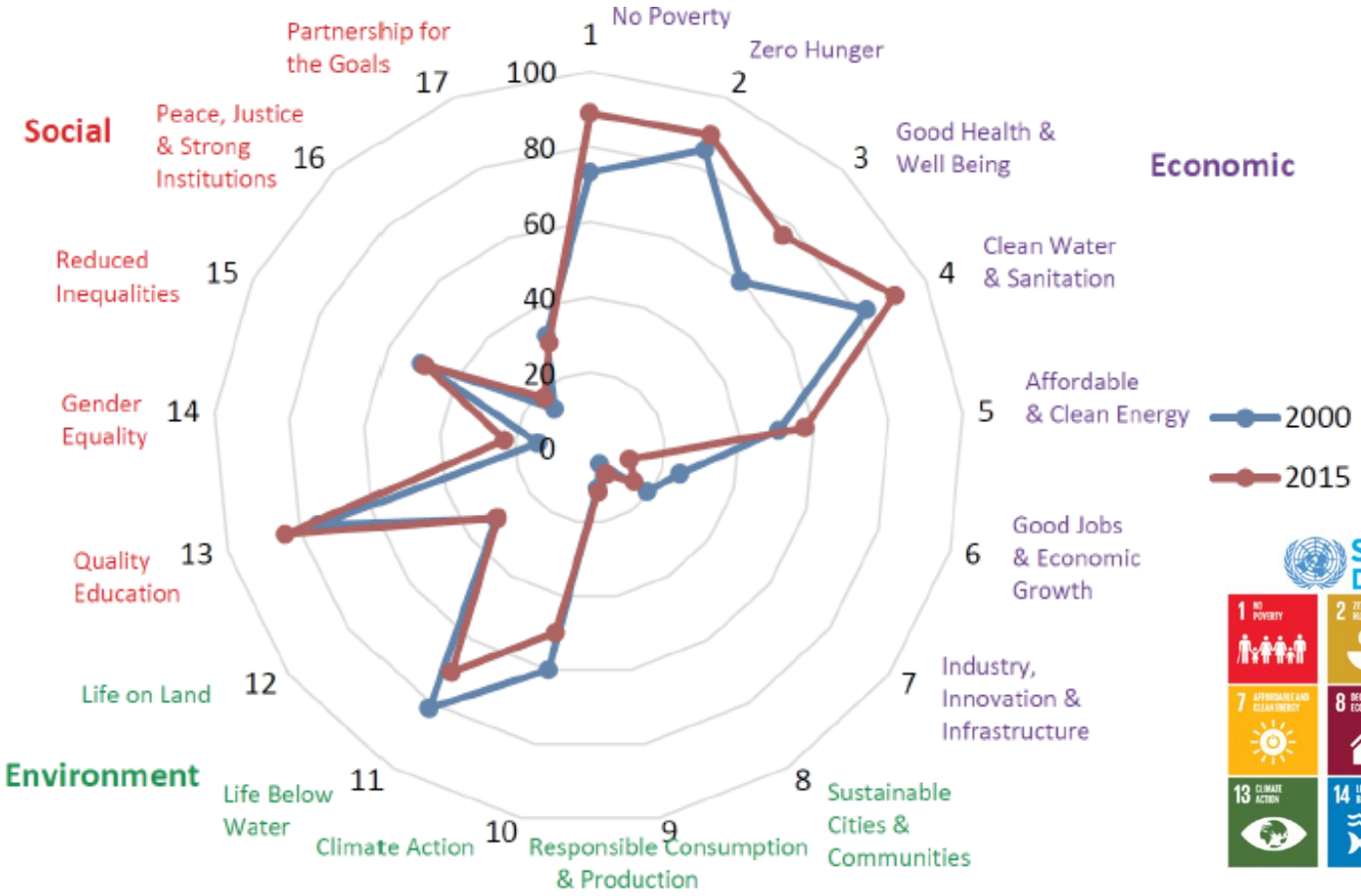
Building better, for longer, with less: “holistic” lessons learned from a lustrum long research on UHPC/UHDC @PoliMi-DICA

Liberato Ferrara

Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano

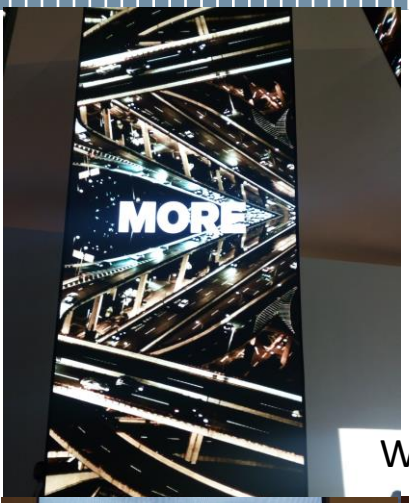
Current «societal» challenges for civil engineering



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

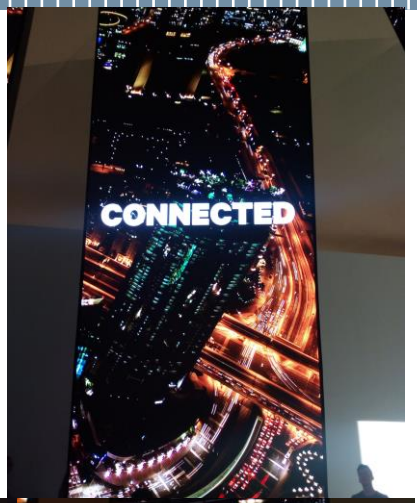


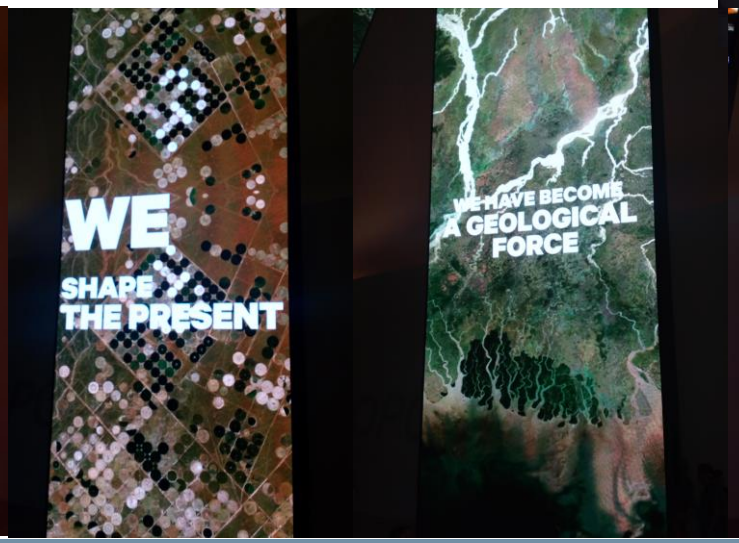
WHICH SCENARIO?

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

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!

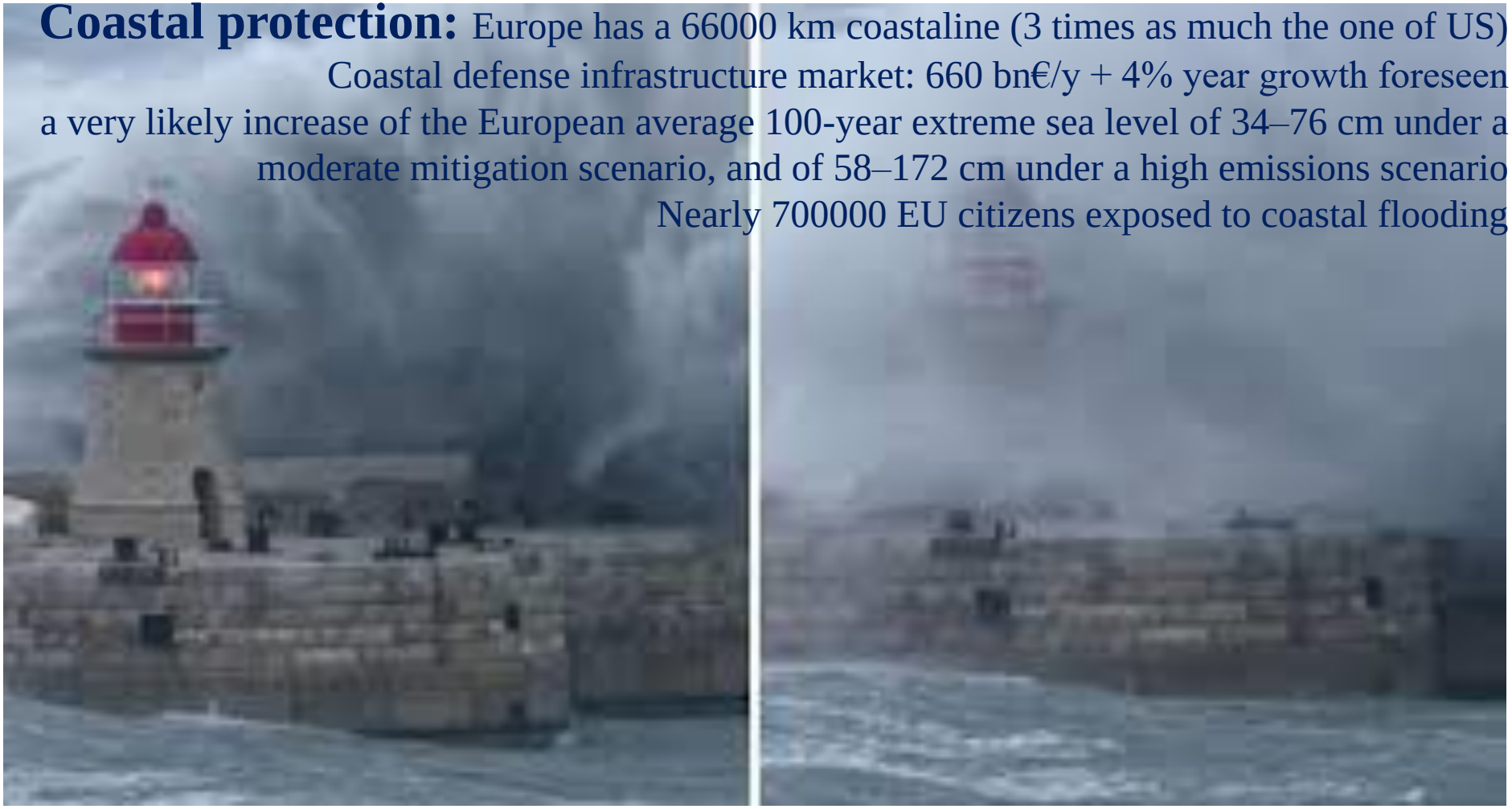
Current «societal» challenges for civil engineering

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

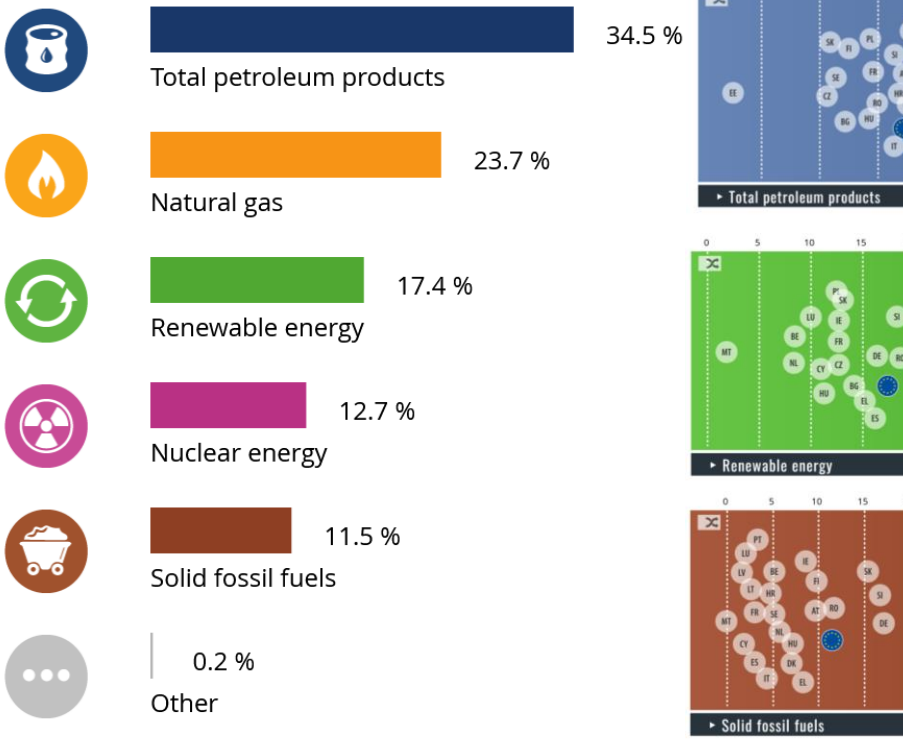
a very likely increase of the European average 100-year extreme sea level of 34–76 cm under a moderate mitigation scenario, and of 58–172 cm under a high emissions scenario

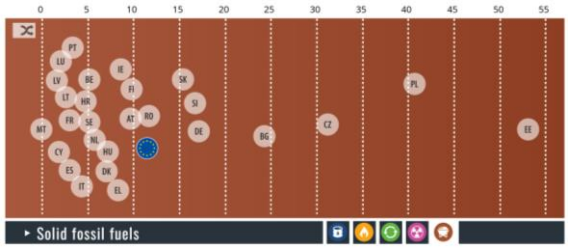
Nearly 700000 EU citizens exposed to coastal flooding

Current «societal» challenges for civil engineering

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

Energy mix for the European Union



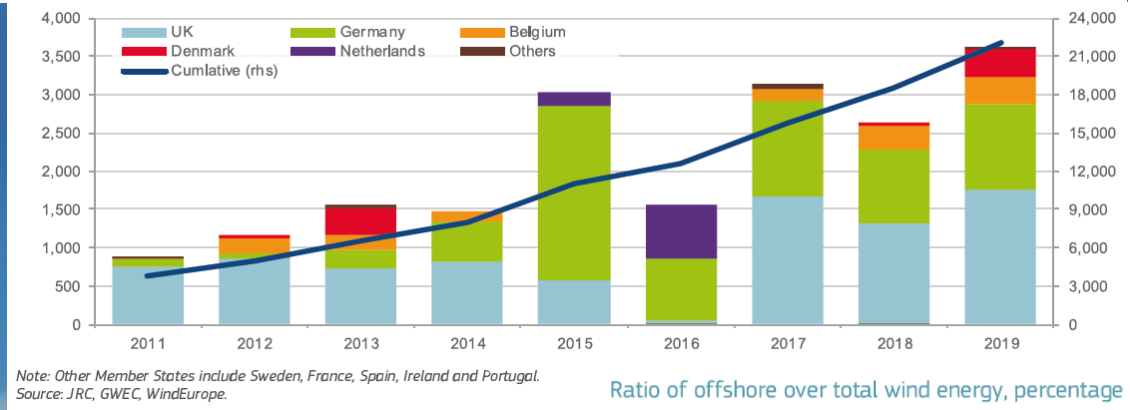


Current «societal» challenges for civil engineering

Green growth: promoting the growth of clean energy production

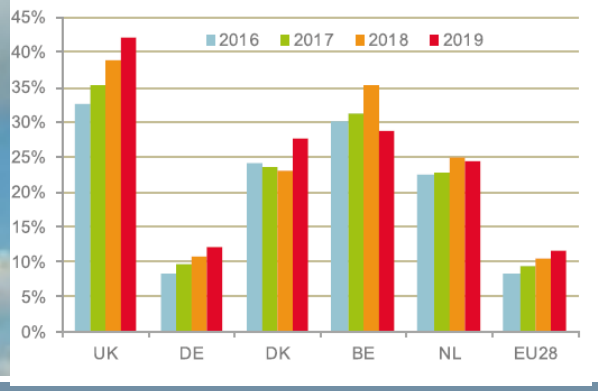
Offshore wind

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

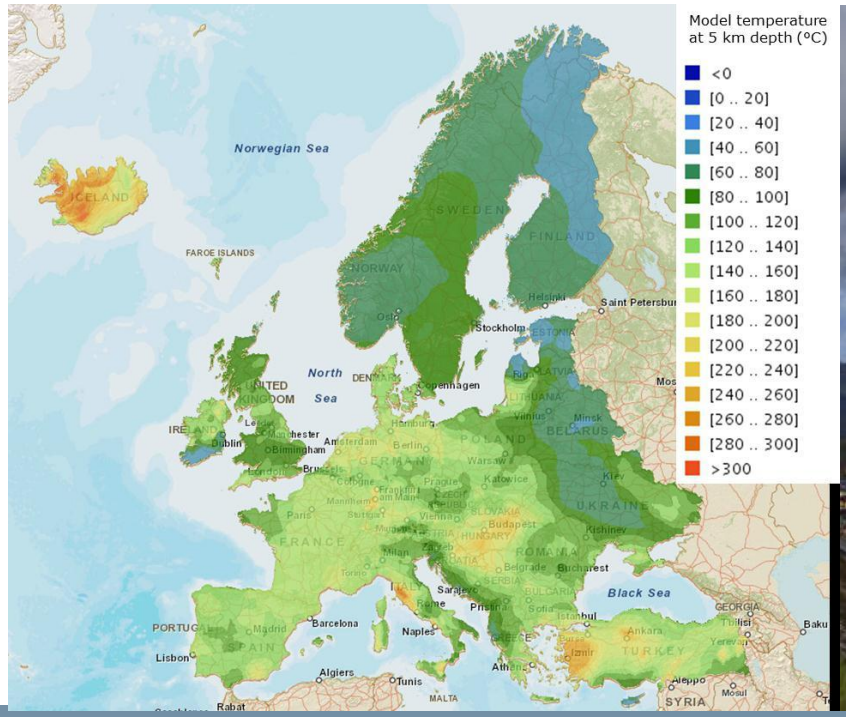


Current «societal» challenges for civil engineering

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

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

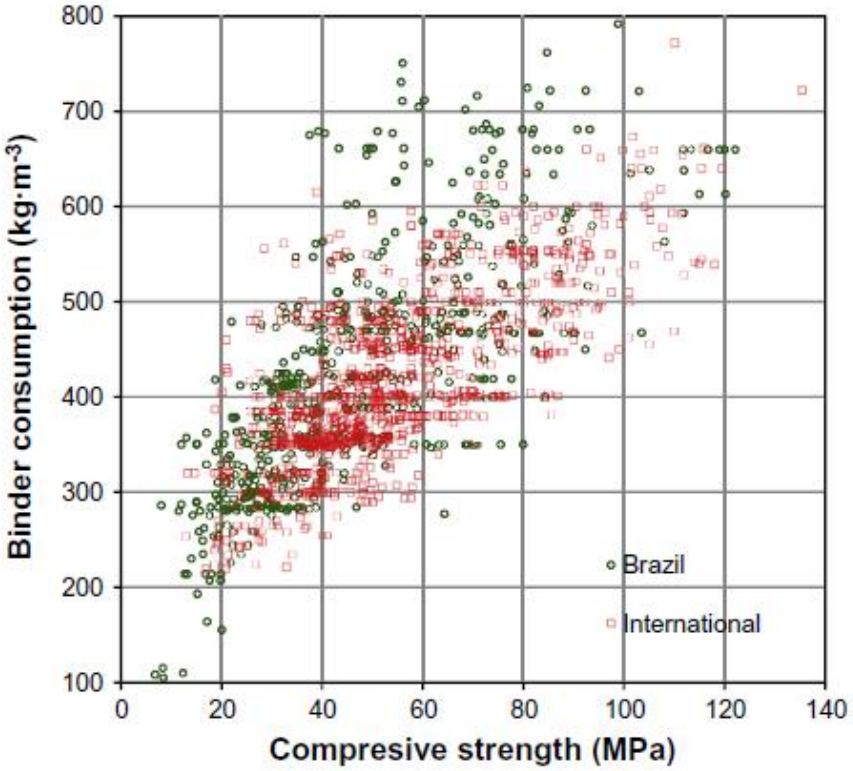
Reduce cement in concrete

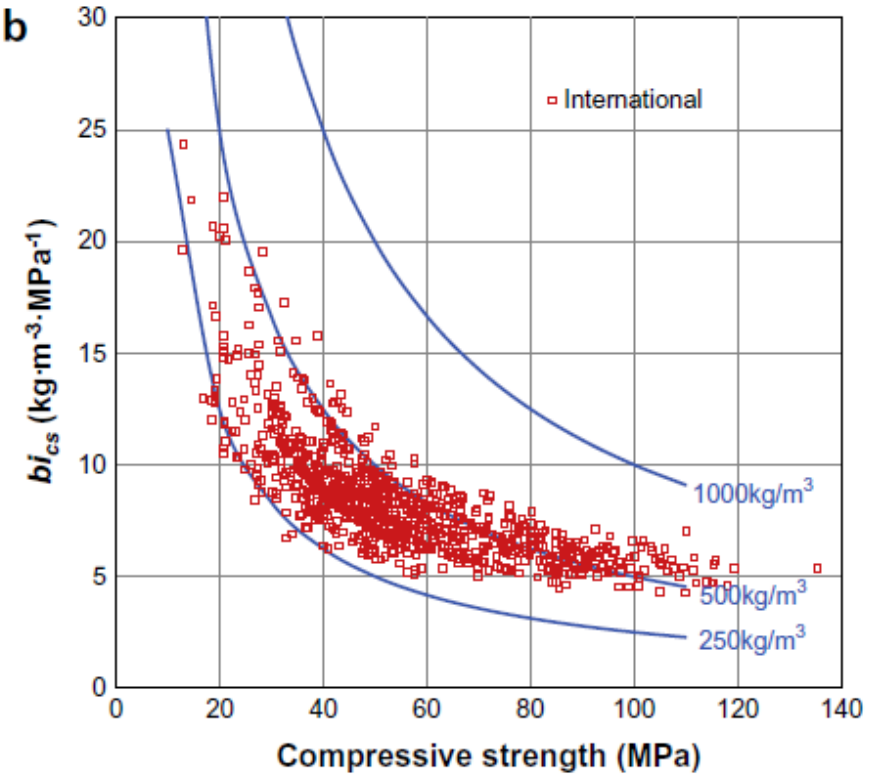
Reduce concrete in buildings and structures

More efficient (re) use of buildings and structures

Current «societal» challenges for civil engineering

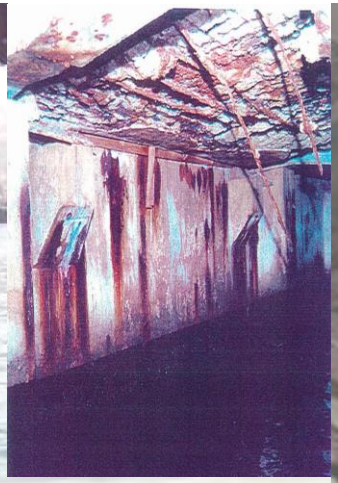
WHICH PERFORMANCE?





Damineli et al., CCC, 2010

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

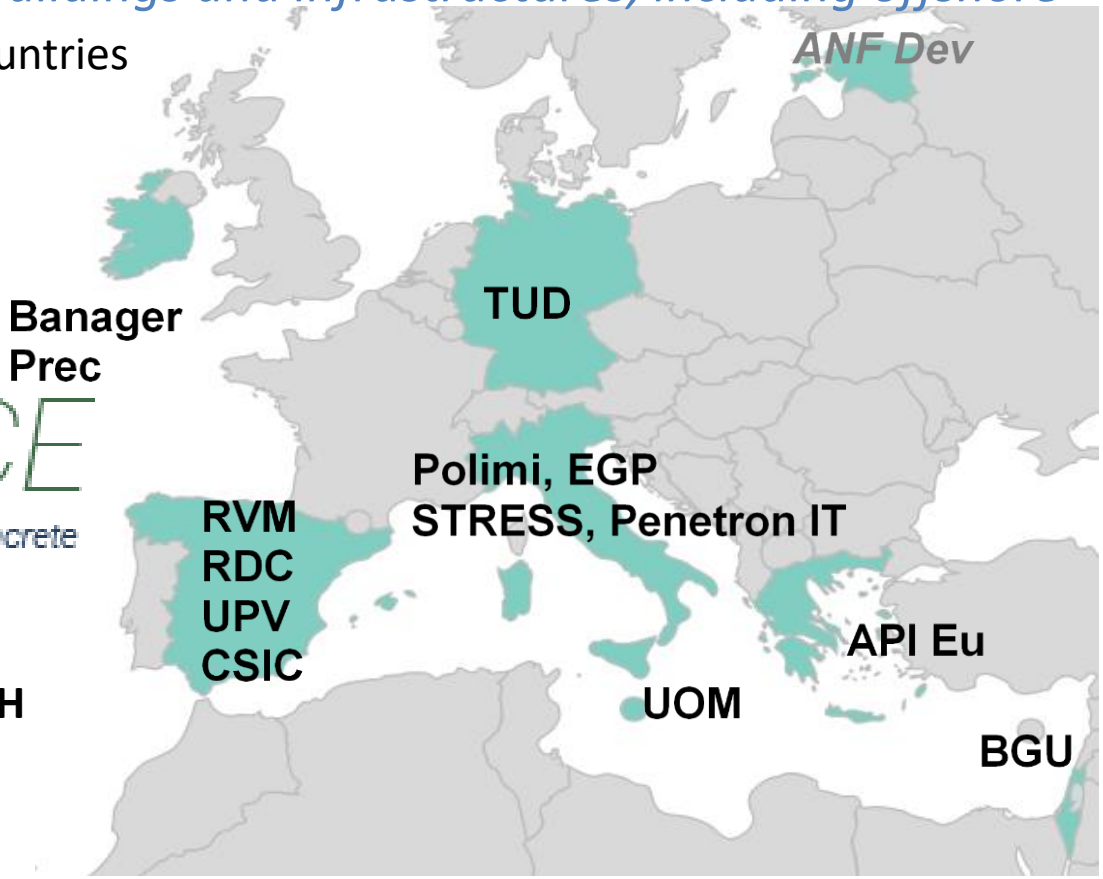
Improved material durability in buildings and infrastructures, including offshore

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

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

TECHNISCHE UNIVERSITÄT DRESDEN

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

PENETRON
TOTAL CONCRETE PROTECTION

L-Università ta' Malta

Ben-Gurion University of the Negev

Large scale end user

API Europe

Universities and research centers

enel Green Power

NAFEN

The whole value-chain of concrete construction industry

rover MARITIME

stress

Infrastructure project and construction

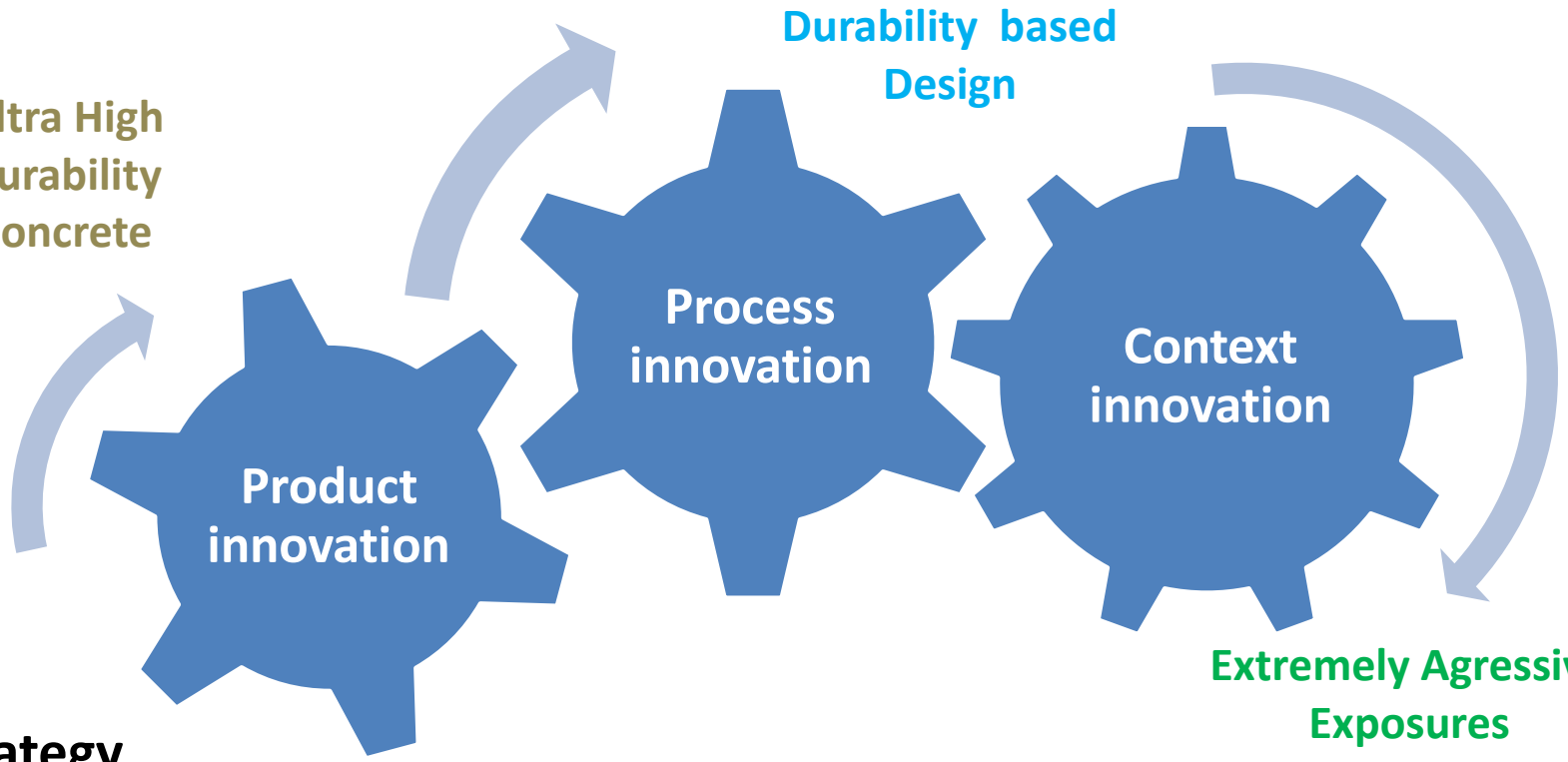
Engineering consultancy - SME

BANAGHER PRECAST CONCRETE

RDC

Precast concrete construction and engineering consultancy - SME

The «ReSHEALience» project 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**

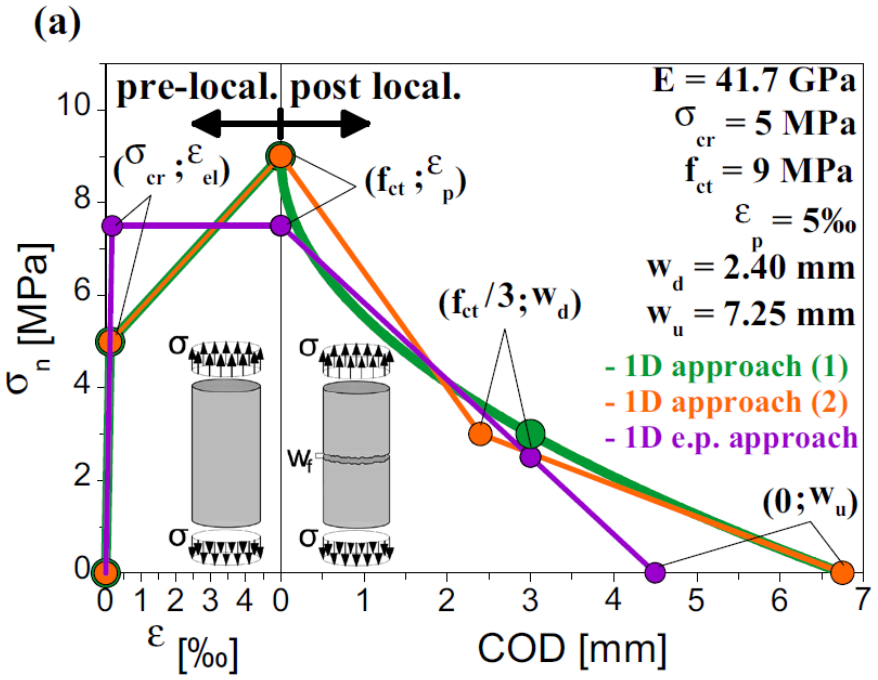
The ReSHEALience project strategy
Material innovation: UHPC

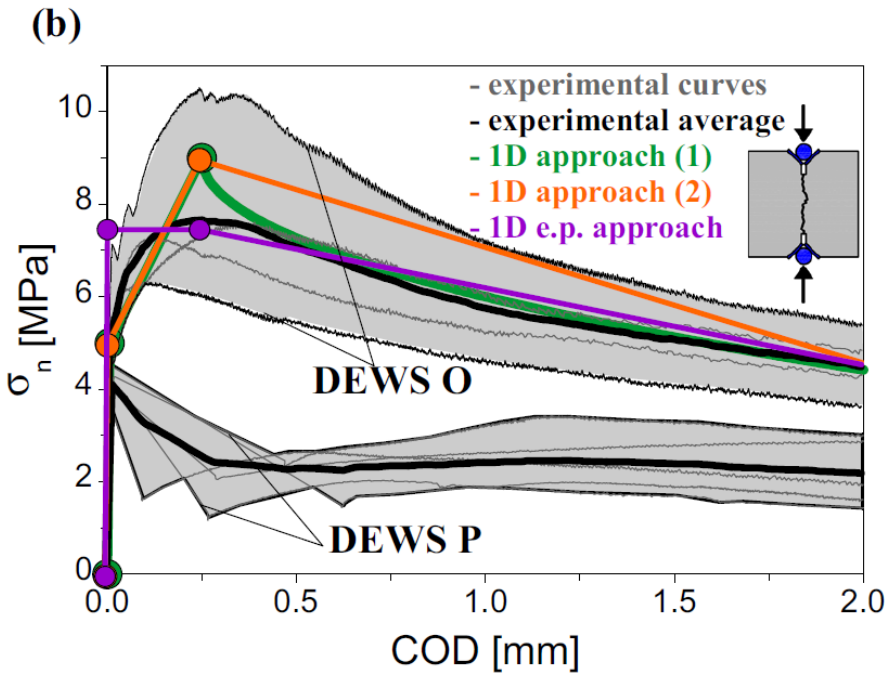
Ultra High Durability Concrete (UHDC): *"strain-hardening fibre/textile reinforced cementitious material with micro- and nano-scale functionalizing constituents, especially added to obtain a high durability in the cracked state under extremely aggressive exposure conditions".*

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

The ReSHEALience project 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

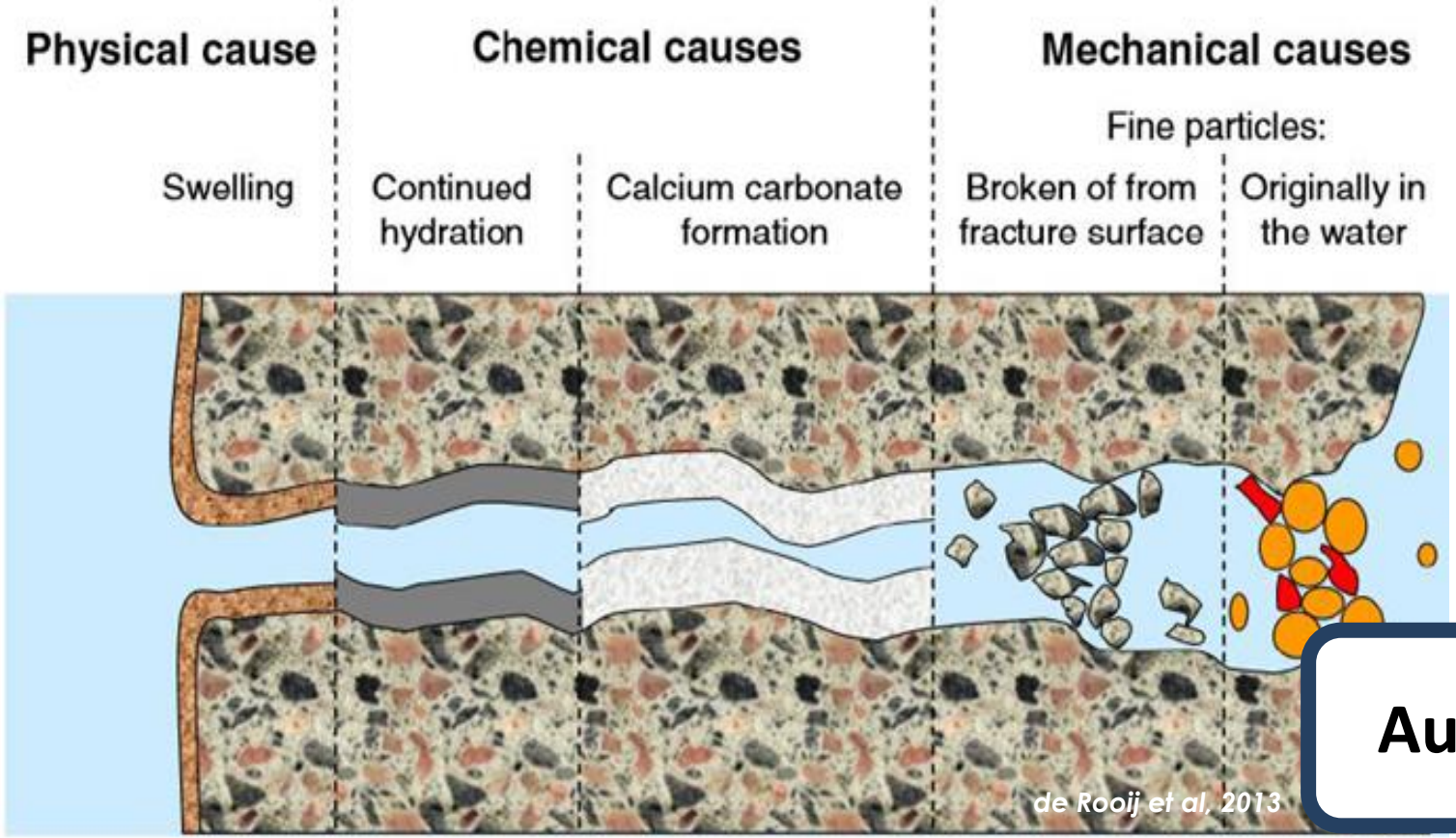




Lo Monte and Ferrara, M&S 2020

The ReSHEALience project concept
Material innovation: from UHPC to UHDC

SELF-HEALING CONCRETE

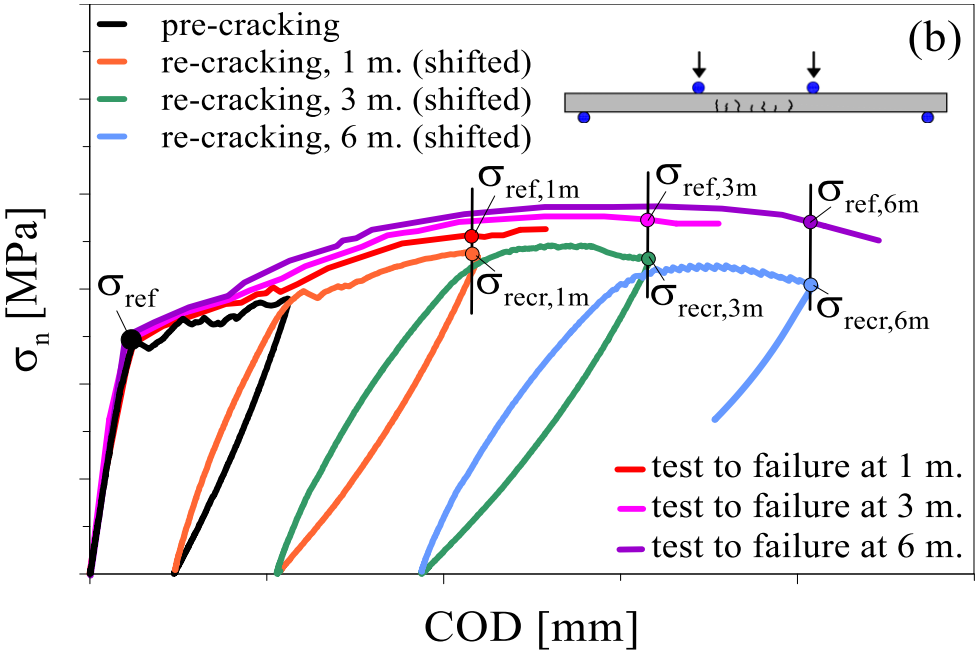


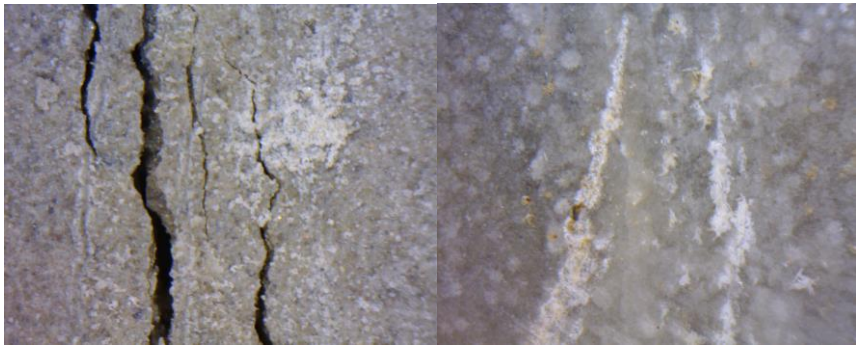
Autogenous

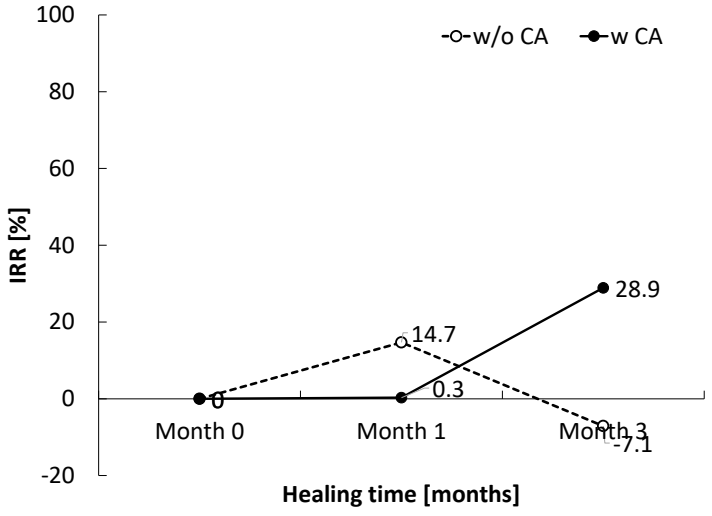
The ReSHEALience project concept
Material innovation: from UHPC to UHDC

Self-healing stimulators: crystalline admixture (Penetron Admix ®)

Stability of mechanical performance – tests made at PoliMi







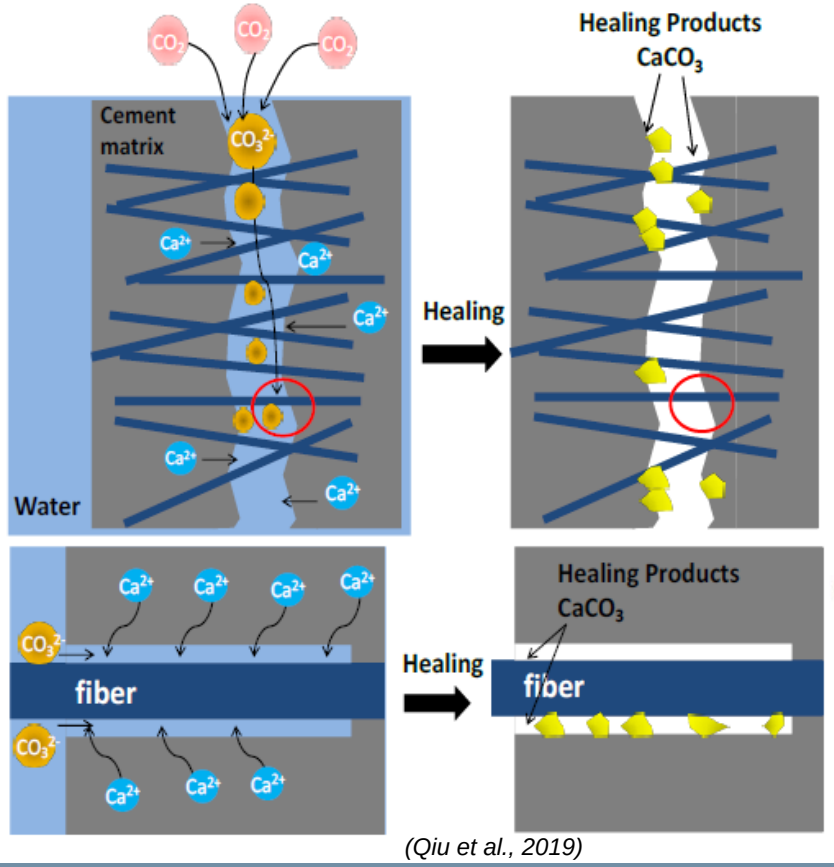
$$IRR[\%] = \left(\frac{\sigma_{recr,i} - \sigma_{ref,i}}{\sigma_{\text{ref}}}\right) \cdot 100$$

Lo Monte and Ferrara, CBM 2021

The ReSHEALience project concept
Material innovation: from UHPC to UHDC

Self-healing stimulators: crystalline admixtures

Stability of mechanical performance – tests on self-levelling UHDC



(Qiu et al., 2019)

EnCoRe
ENvironmentally-friendly solutions for COncrete with REcycled and natural components

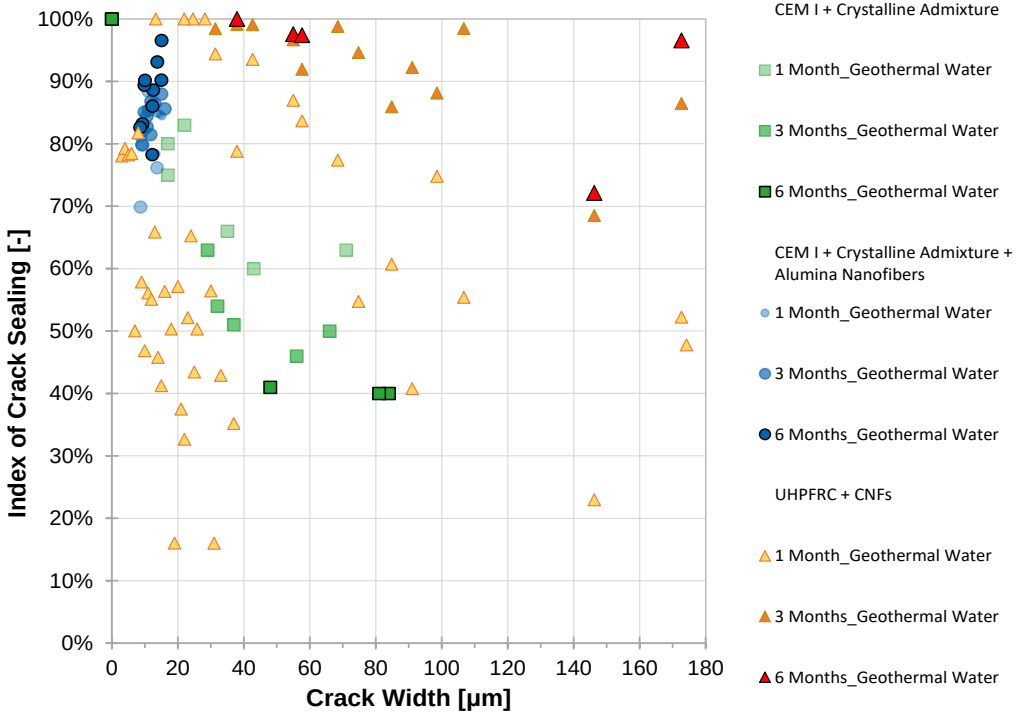
POLITECNICO MILANO 1863

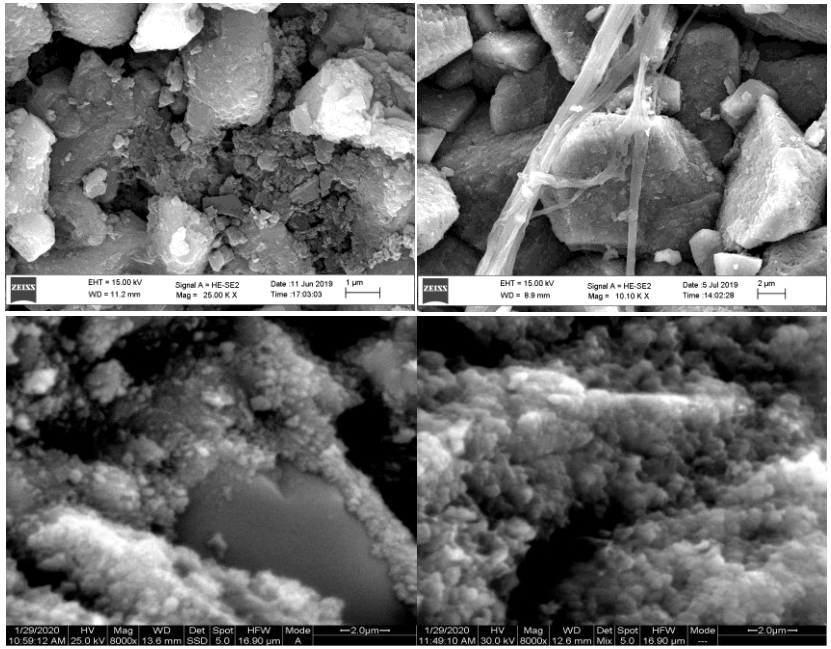
Universidade Federal do Rio de Janeiro

Al-Obaidi et al., M&S submitted

The ReSHEALience project concept
Material innovation: from UHPC to UHDC

Synergy between crystalline admixtures (Penetron Admix ®) and alumina nanofibres (Nafen®) or cellulose nanofibrils/crystals(API Europe®) effectiveness of (im()permeability recovery: tests made at PoliMi

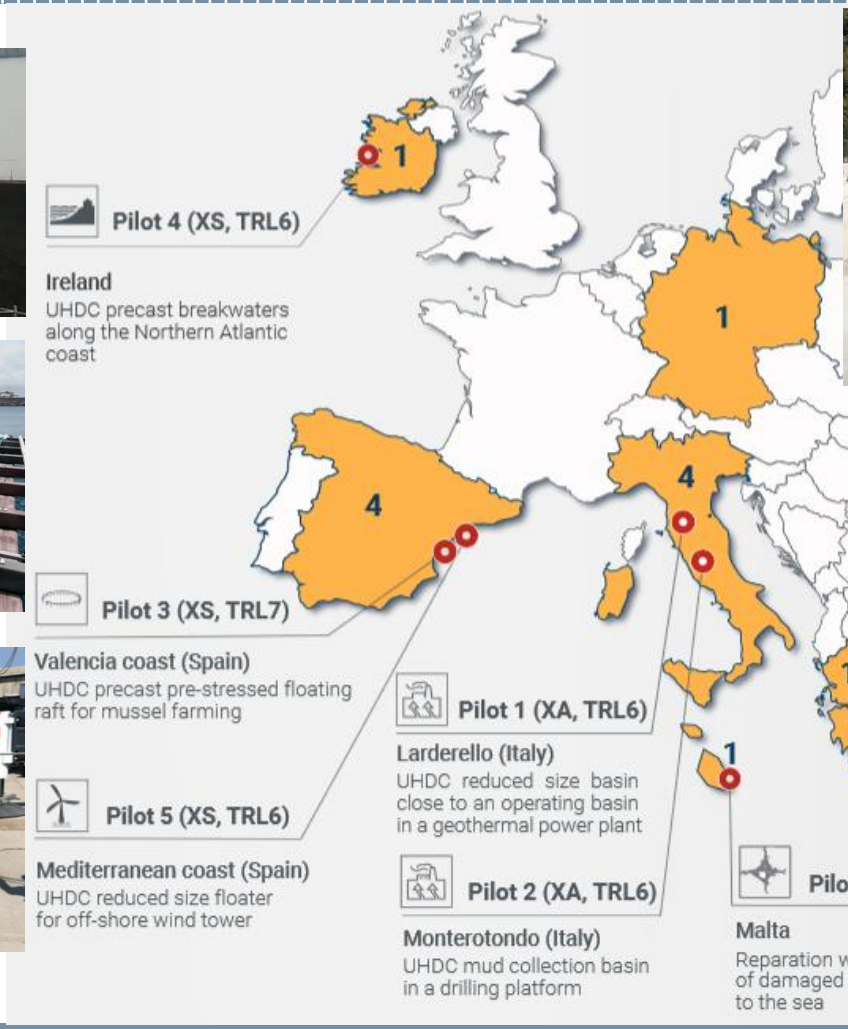


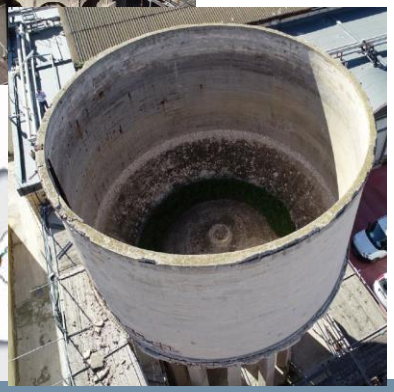


Cuenca et al., CBM 2021, CCR 2022, CBM 2023

The ReSHEALience project strategy
Process innovation: upscaling

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





Liberato Ferrara, Department of Civil and Environmental Engineering

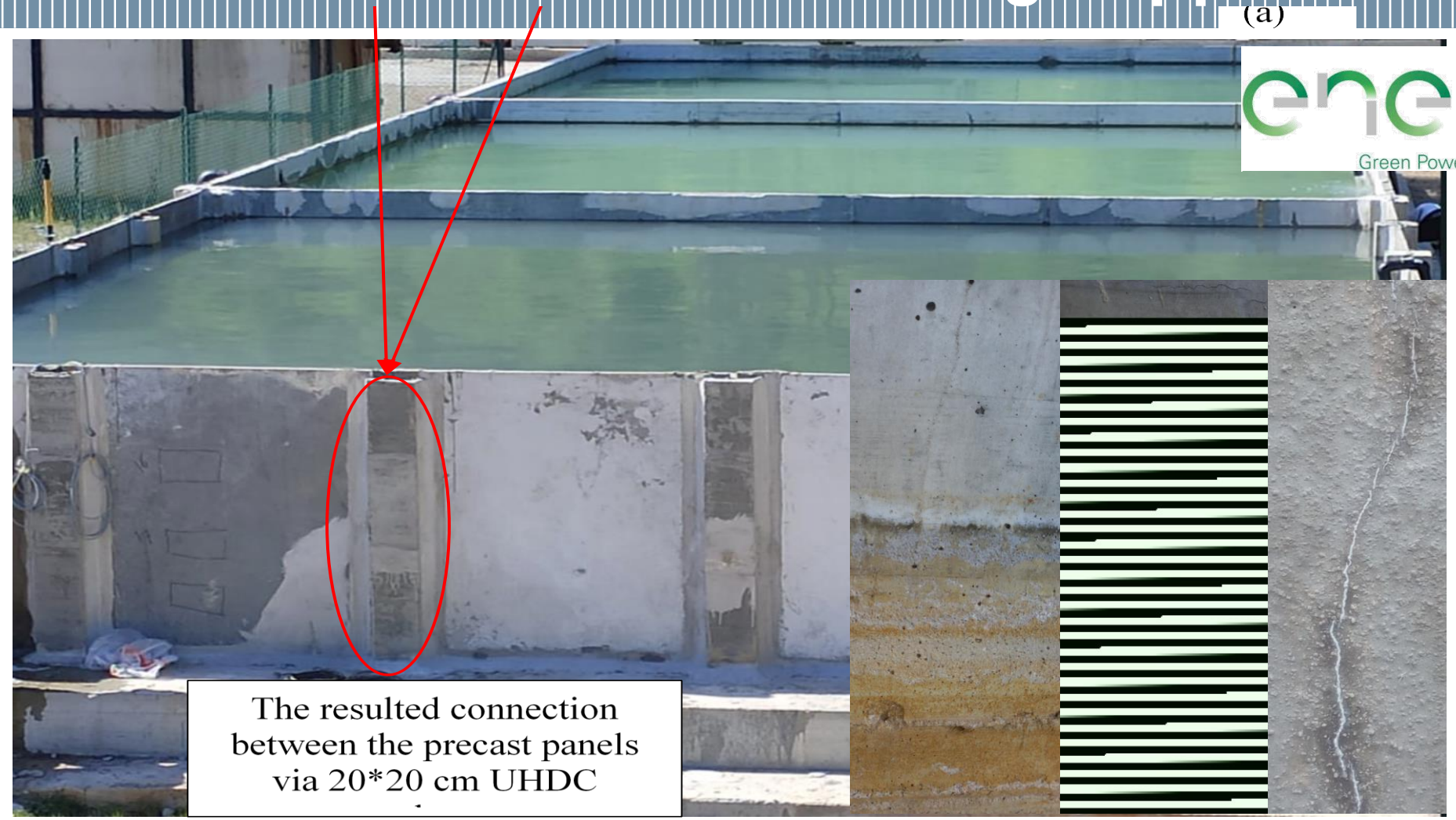
POLITECNICO MILANO 1863

The ReSHEALience project strategy: towards a novel holistic design approach

Liberato Ferrara, Department of Civil and Environmental Engineering

POLITECNICO MILANO 1863

The ReSHEALience project strategy: towards a novel holistic design approach



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*

Reduce cement in concrete?

The ReSHEALience project strategy: towards a novel holistic design approach

Reduce cement in concrete?

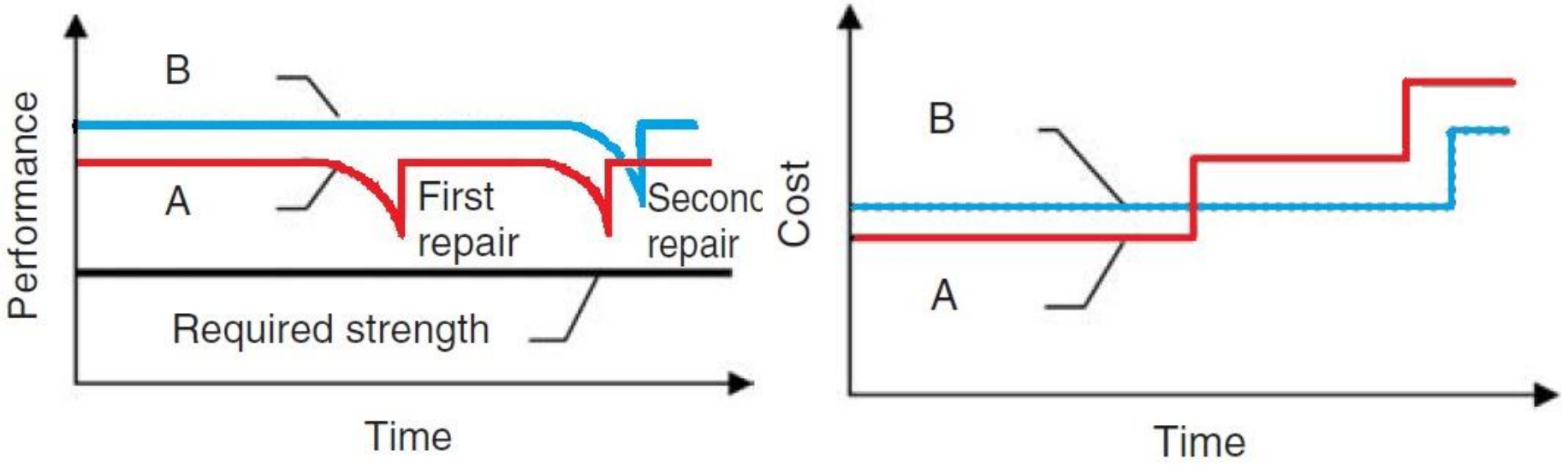
350 kg/m3 cement
10 cm thickness
35 kg/m^2 cement

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

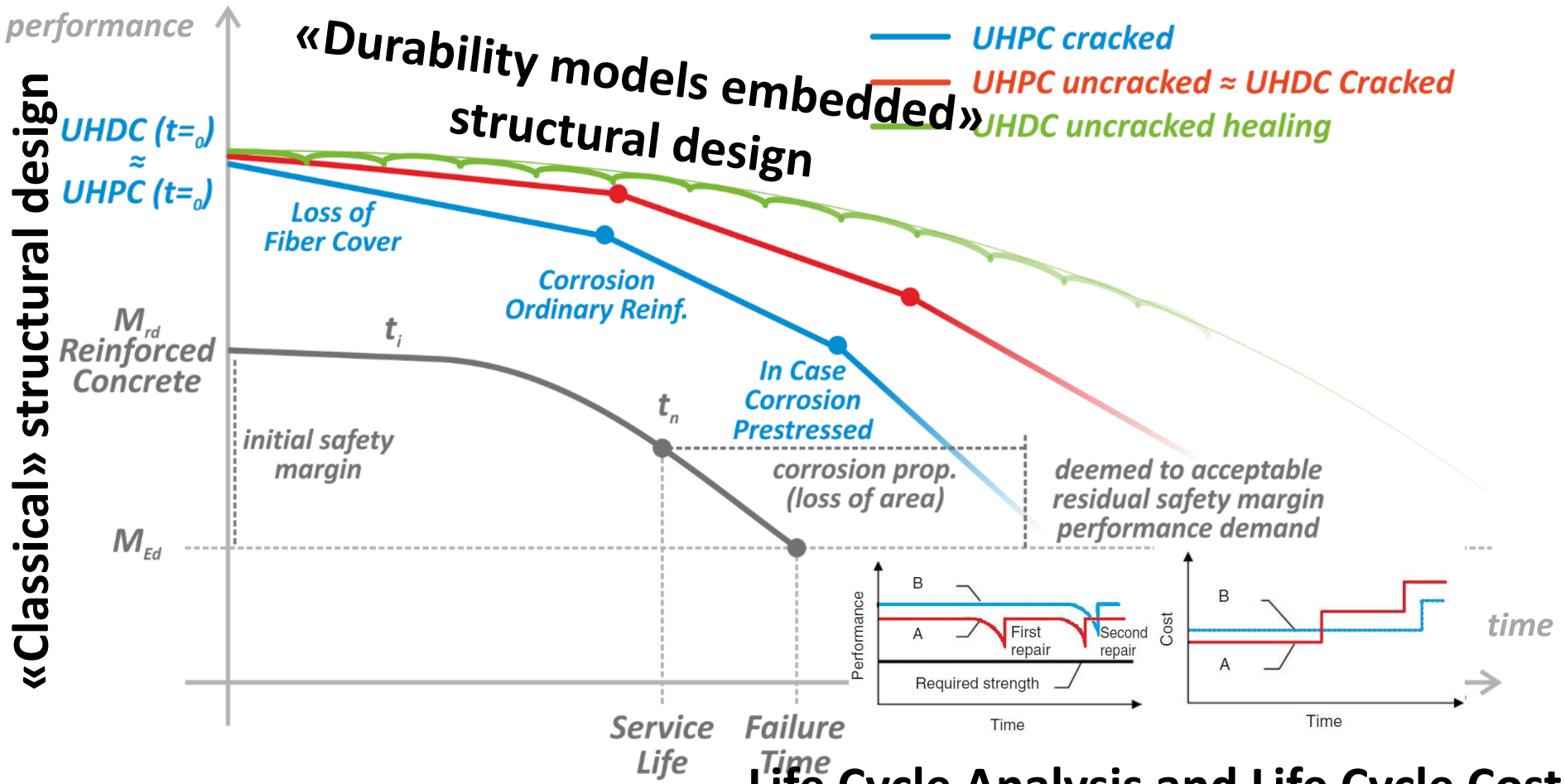
Reduce concrete in structures!

The ReSHEALience project strategy: towards a novel holistic design approach

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 under extremely aggressive exposure conditions".*



The ReSHEALience project strategy: towards a novel holistic design approach

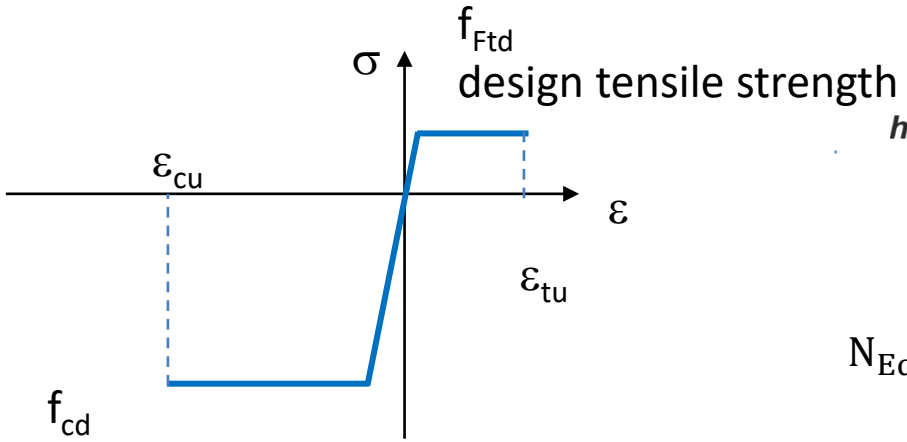


Design for durability

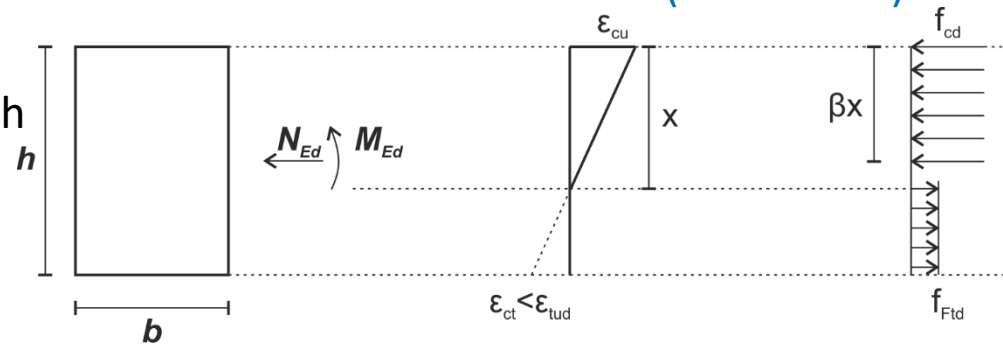
How can we «scale up» to higher level approaches?

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

UHDC design constitutive model



UHDC 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

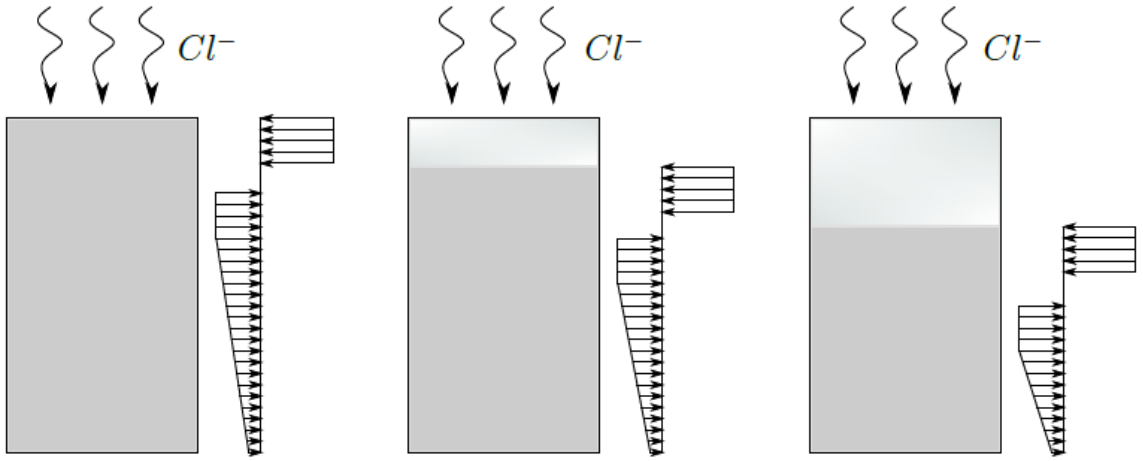
The ReSHEALience project concept
Process innovation: a holistic design approach

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 attack



Al-Obaidi et al., Infrastructures, 2020

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 attack

$$M_{Ed} = 10\ kN/m^3 \times (\sqrt[3]{\gamma_G}\ 1.3\ m)^3/6 = \gamma_G\ 3.7\ kNm/m \cong 5\ kNm/m$$

$$M_{Rd}(t_0) = f_{Ftd} \cdot b \frac{h^2}{2} = 5.6\ N/mm^2\ (1m) \frac{(60\ mm)^2}{2} = 10.1\ kNm/m$$

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

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

Al-Obaidi et al., Infrastructures, 2020

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 $M_{Rd}(t)$? – sulfate attack

$$M_{Ed} = 10\ kN/m^3 \times (\sqrt[3]{\gamma_G}\ 1.3\ m)^3/6 = \gamma_G\ 3.7\ kNm/m \cong 5\ kNm/m$$

$$M_{Rd}(t_0) = f_{Ftd} \cdot b \frac{h^2}{2} = 5.6\ N/mm^2\ (1m) \frac{(60\ mm)^2}{2} = 10.1\ kNm/m$$

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

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

Al-Obaidi et al., Infrastructures, 2020

The ReSHEALience project concept
Process innovation: a 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 $M_{Rd}(t)$? – sulfate attack

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

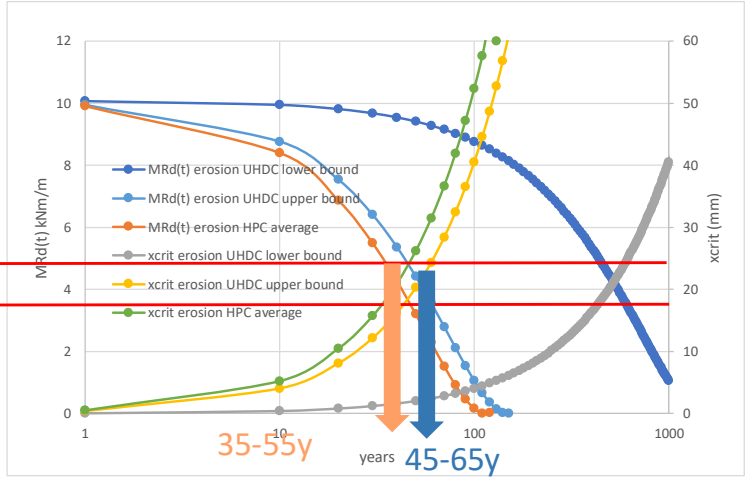
$$Erosion:\ x_{crit} = a\sqrt{t*} + ke\ t \cong ke\ t$$

M_{Ed}(ULS-γ_G=1.35) = 5 kNm/m

x_{crit}(ULS-γ_G=1.35) = 18 mm – residual section thickness 42 mm

M_{Ed}(ULS-γ_G=1.0) = 3.7 kNm/m

x_{crit}(ULS-γ_G=1.0) = 24 mm – residual section thickness 26 mm

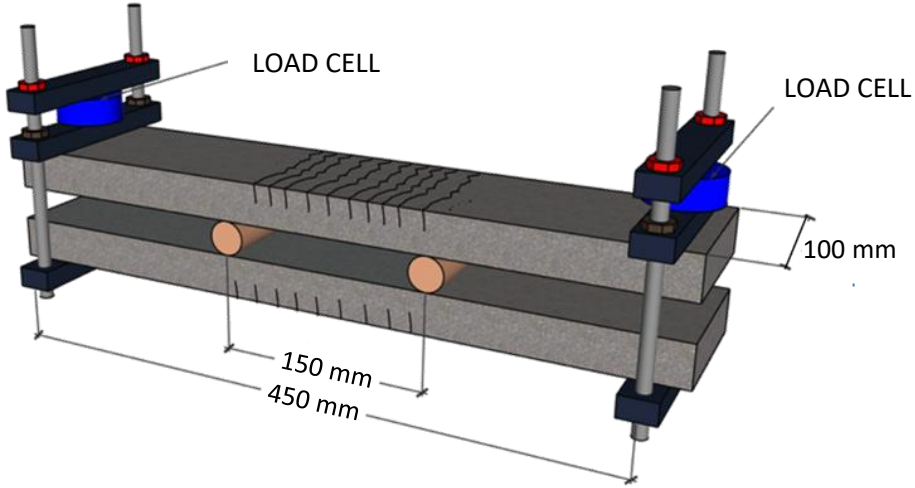


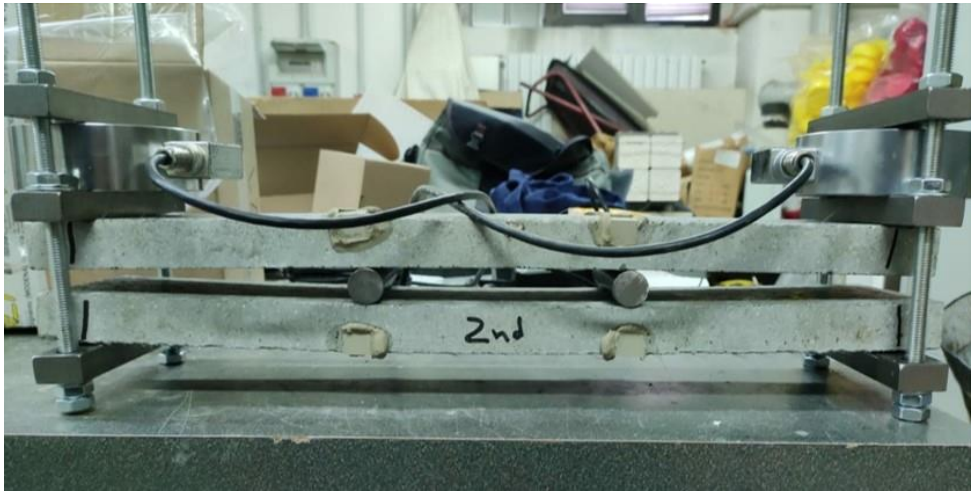
Al-Obaidi et al., Infrastructures, 2020

The ReSHEALience project concept
Process innovation: a holistic design approach

Design for durability

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





Davolio et al., CCC 2023, submitted
Al Obaidi et al. Proc SHCC5-2022

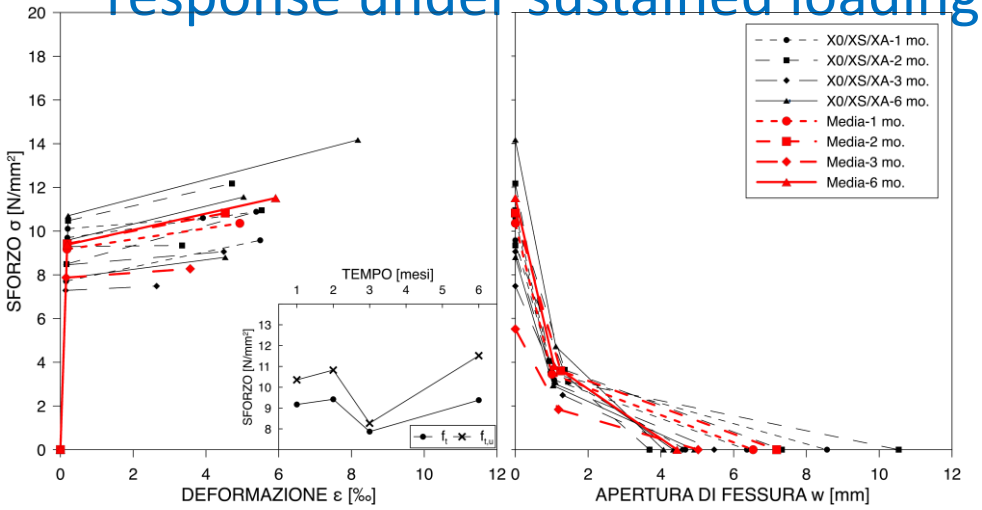
The ReSHEALience project concept
Process innovation: a holistic design approach

Design for durability

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

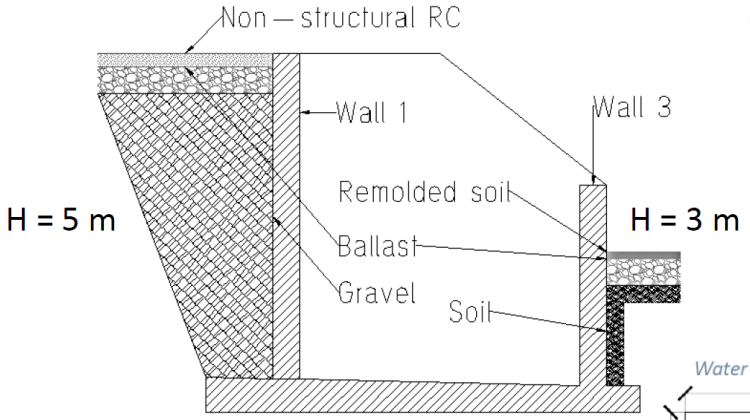
What direct durability indicators related to specific degradation mechanisms mean in terms of structural performance?

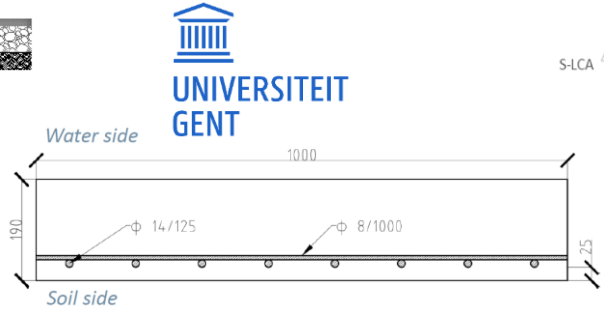
How do we evaluate $M_{Rd}(t)$? – evolution of material constitutive response under sustained loading in aggressive scenarios

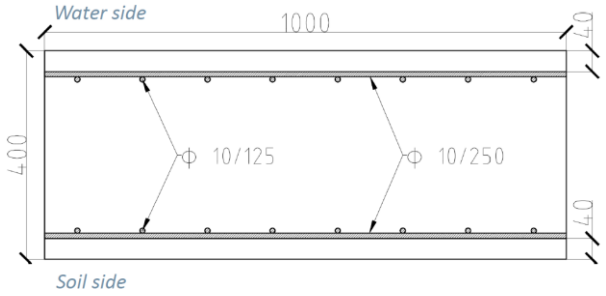


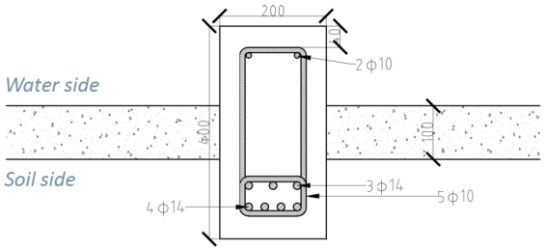
Davolio et al, 2023 CCC submitted

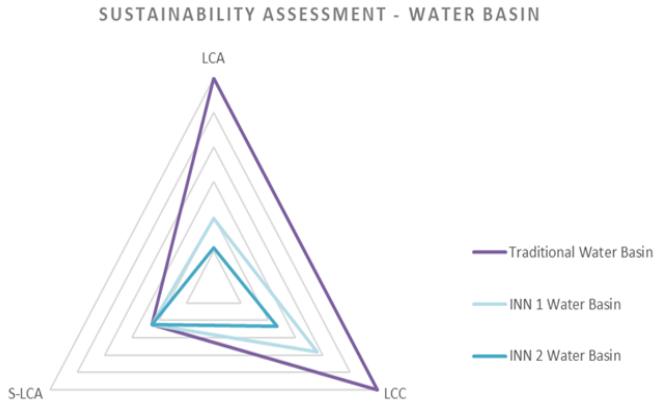
ReSHEALience project: concluding remarks in a durability and LCA based «structural design» nutshell

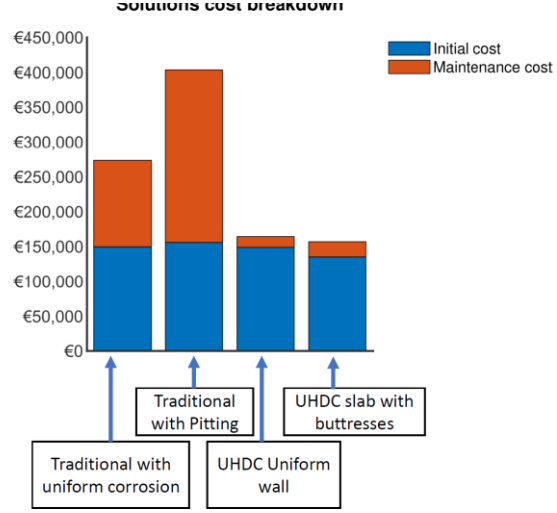










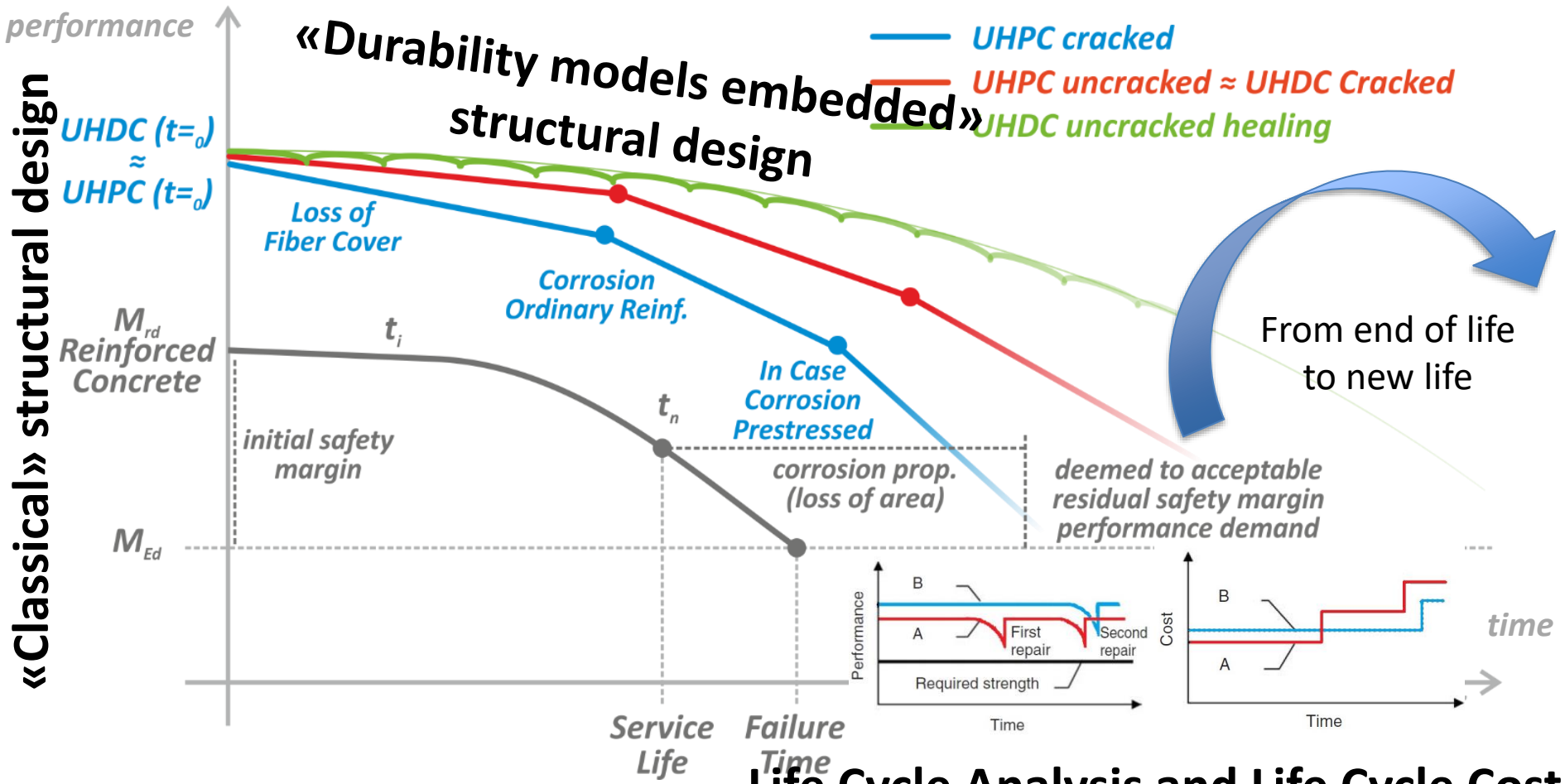


di Summa et al., RILEM week 2022

SMARTINCS

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 ReSHEALience project concept
Process innovation: Durability based Design



Life Cycle Analysis and Life Cycle Cost

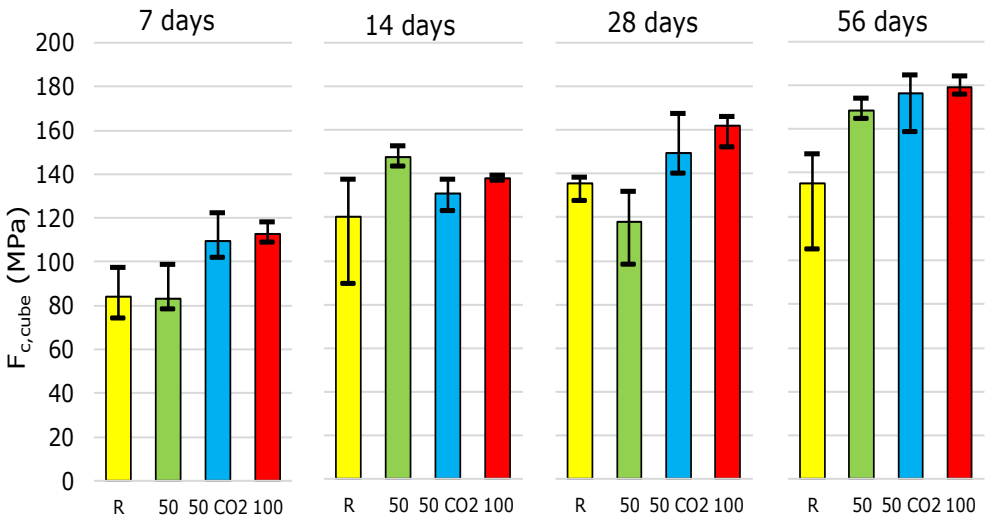
The ReSHEALience project concept
Process innovation: re/up cycling

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

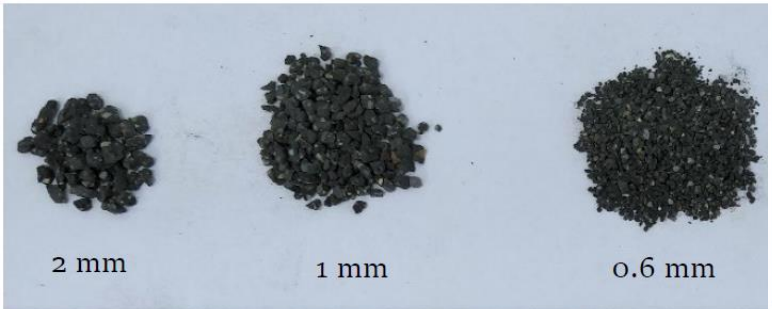
L-Università ta' Malta

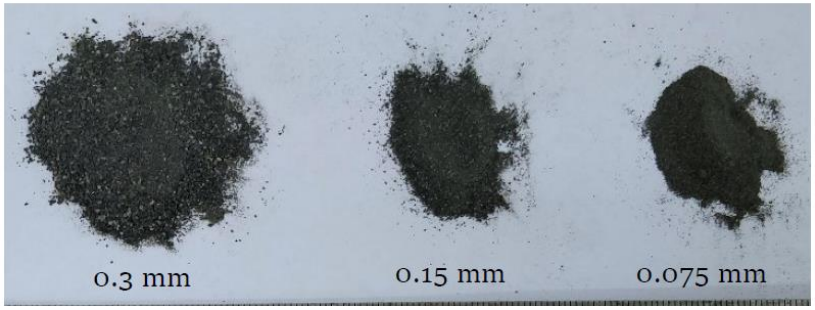
POLITECNICO MILANO 1863

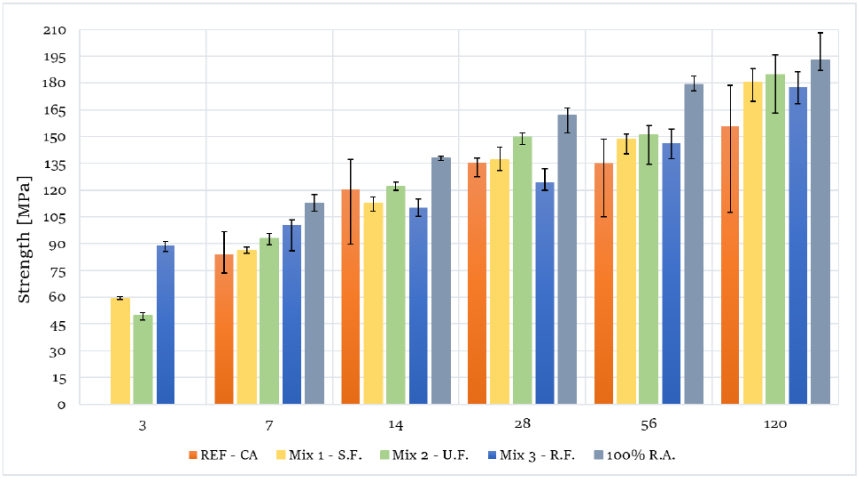
Borg et al., FBE, 2021

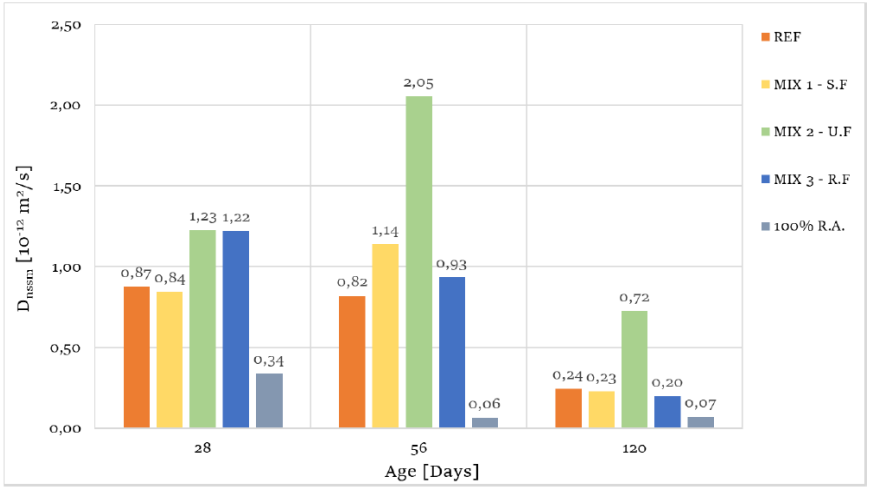


The ReSHEALience project concept
Process innovation: re/up cycling









Ferrara et al., fib Symp. 2023

L-Università ta' Malta

POLITECNICO MILANO 1863

The ReSHEALience project follow-up

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

Kannikachalam et al., ACI MatJ, 2023

Current «societal» challenges for civil engineering

Reflection Paper addresses the role of materials in the post-covid society

Published on 24.09.2020 by EMMC - European Commission - A4M_Alliance for Materials - EUMAT

"The role of Materials in the post-COVID society"

A reflection on how Materials will enable solutions for a healthy, safe, and resilient society to achieve a sustainable, stable, and stronger economy, able to respond to citizen's demands.

… to create a less dependent, more resilient European economy by guaranteeing raw material supplies, by ensuring higher materials durability, higher energy efficiency, higher degrees of materials re-cycling and re-use and by material-saving through optimized products by design with enhanced repair

Current «societal» challenges for civil engineering

EMMC 2030 advanced materials manifesto

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**.

https://emmc.eu/wp-content/uploads/2022/02/advanced-materials-2030-manifesto.pdf

on behalf of the ReSHEALience consortium

Liberato Ferrara, Department of Civil and Environmental Engineering

POLITECNICO MILANO 1863

… 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

POLITECNICO MILANO 1863