
# Nanofiber Reinforced UHPC for Enhanced Crack Control and Enhanced Durability

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# Current «societal» challenges for civil engineering

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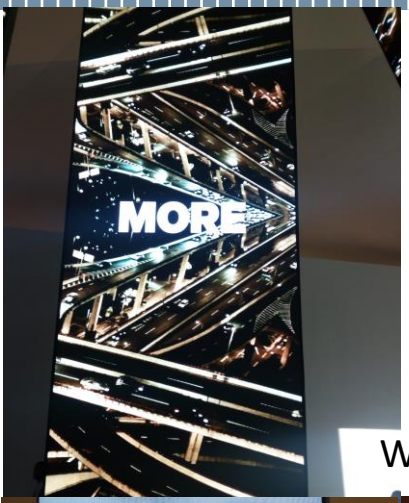
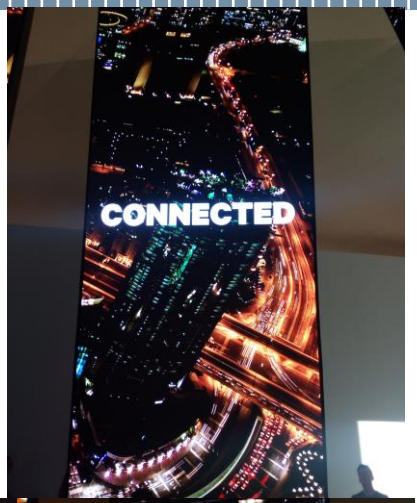



## WHICH SCENARIO?

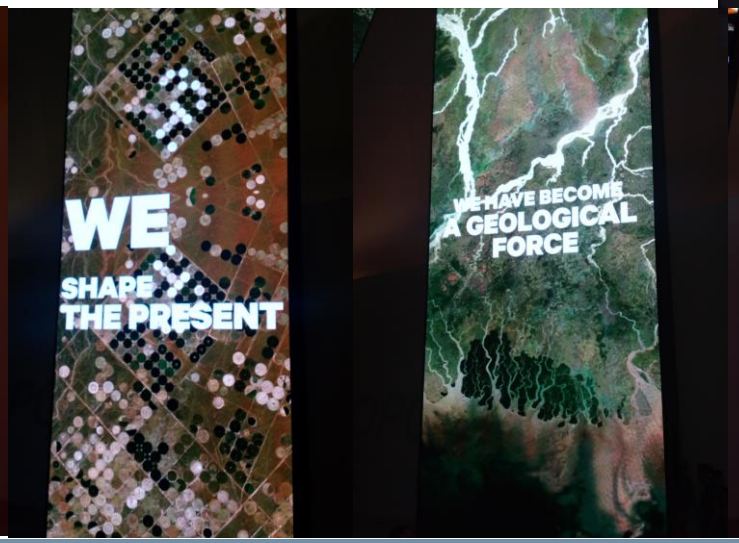
55% world population lives in urban areas
(up to 80% in high income countries)

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**

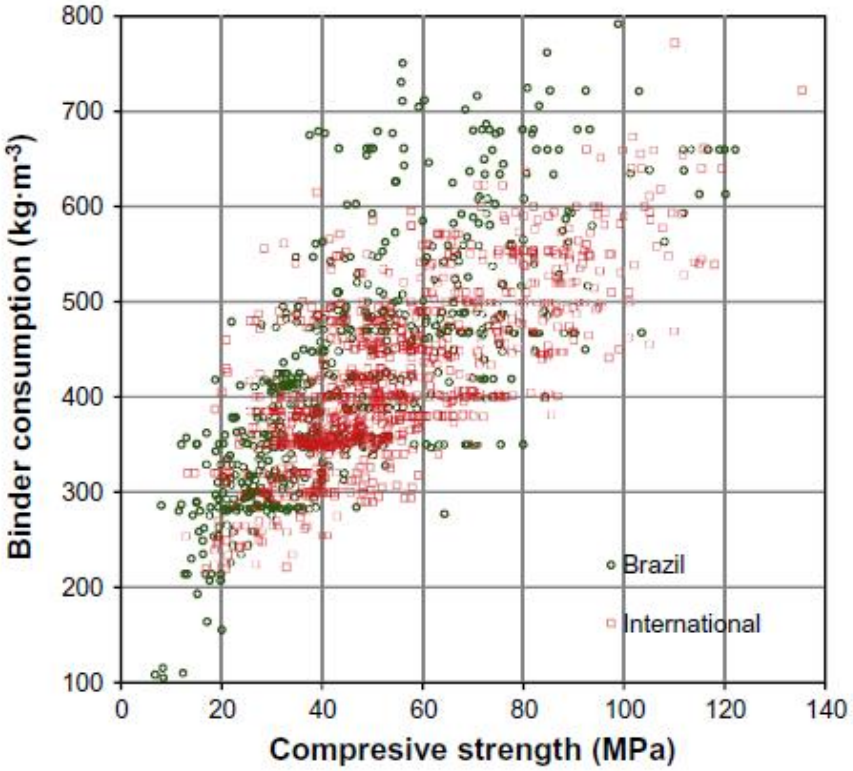
**Reduce cement in concrete**

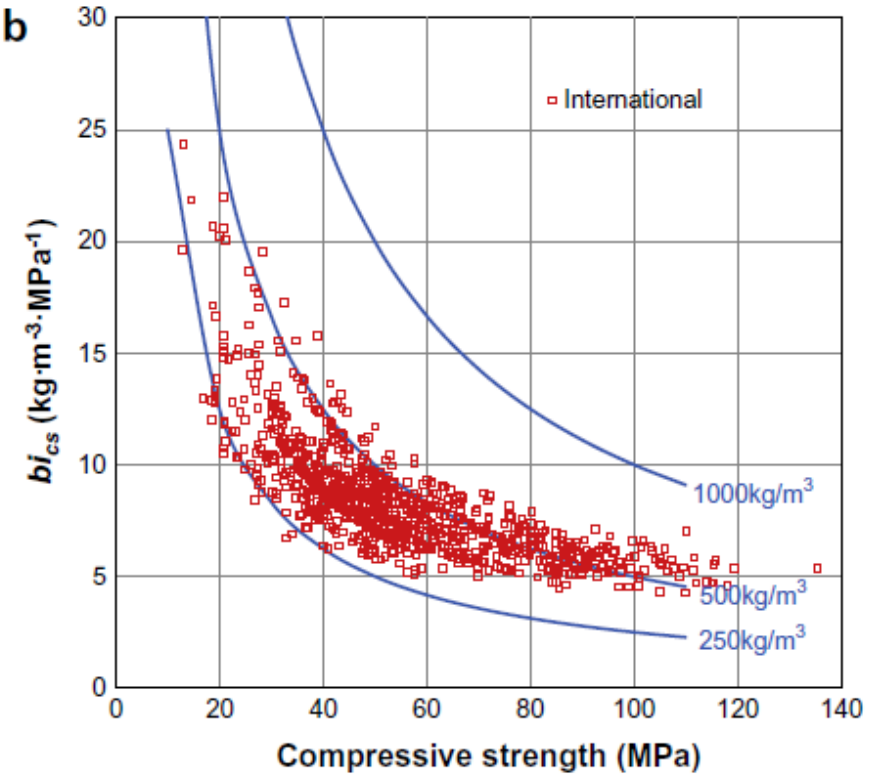
**Reduce concrete in buildings and structures**

**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

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

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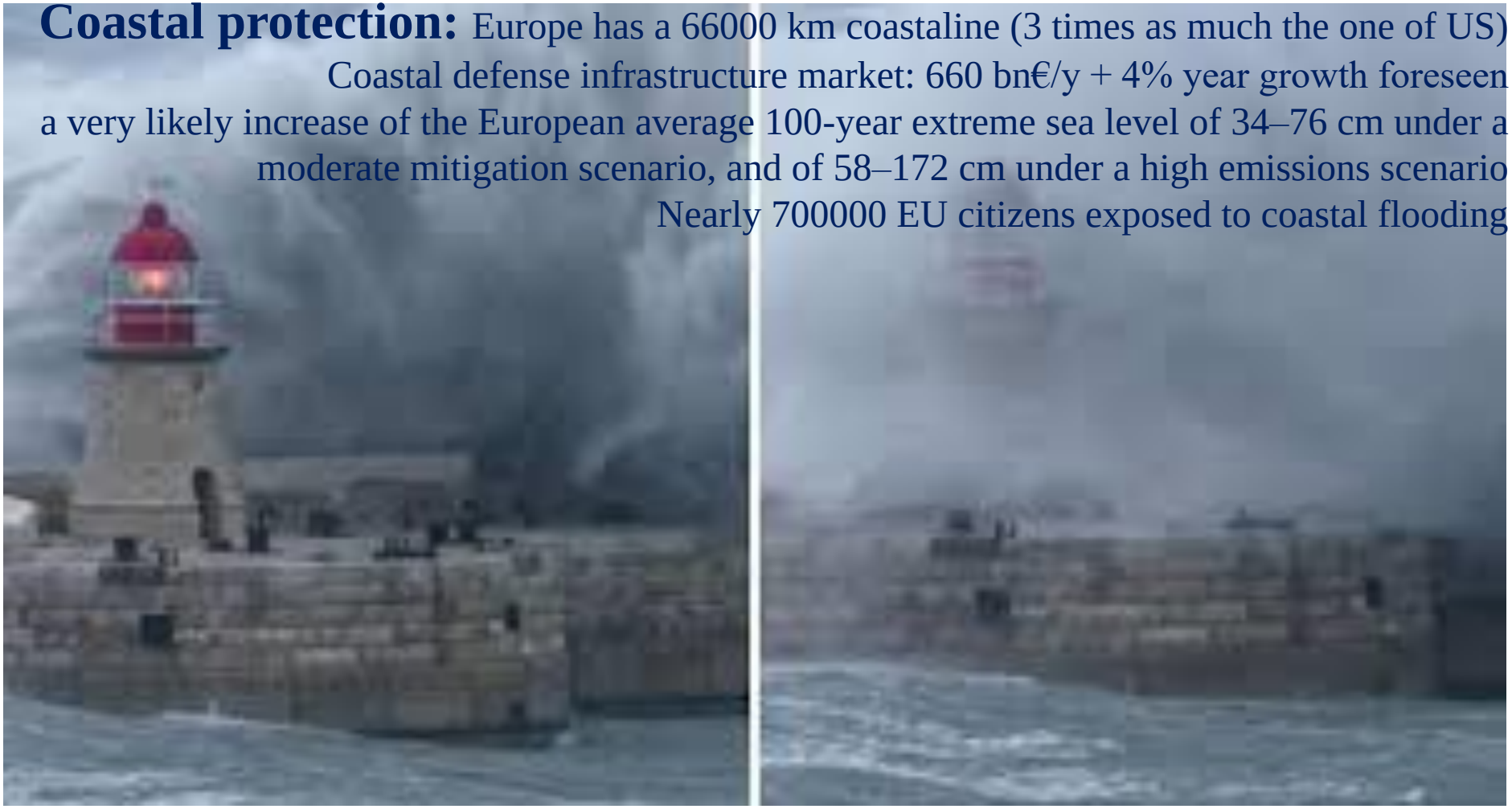
# Current «societal» challenges for civil engineering



**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

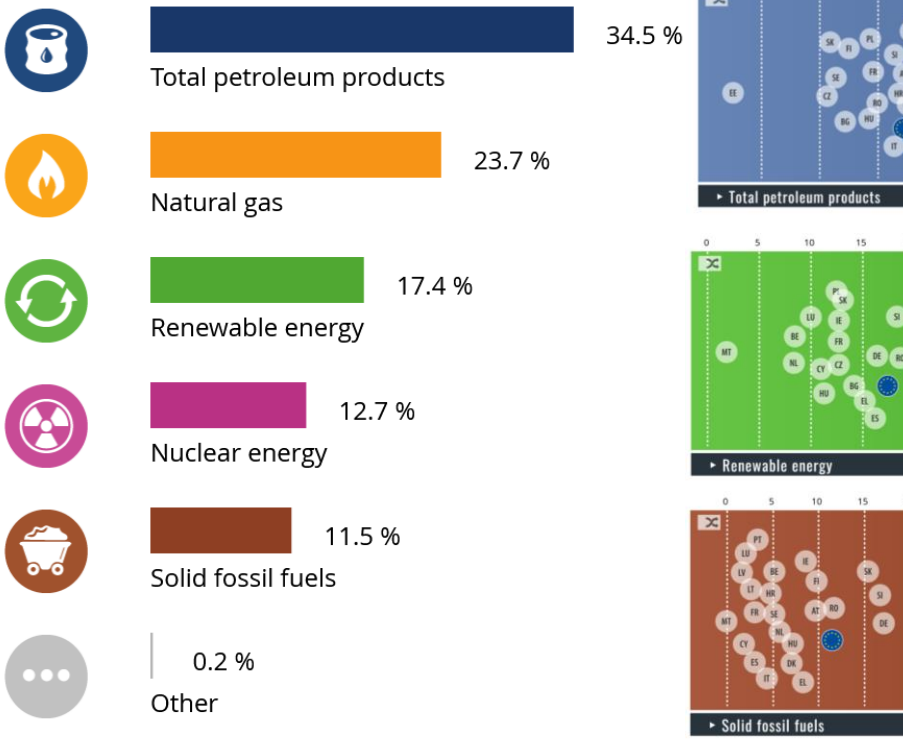
a very likely increase of the European average 100-year extreme sea level of 34–76 cm under a moderate mitigation scenario, and of 58–172 cm under a high emissions scenario

Nearly 700000 EU citizens exposed to coastal flooding

# Current «societal» challenges for civil engineering

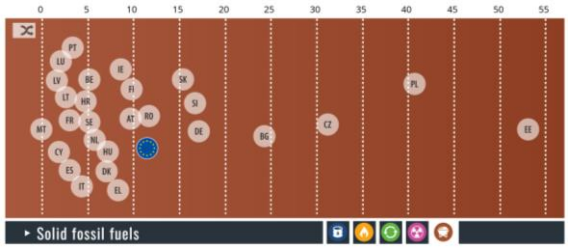
https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html

## Energy mix for the European Union







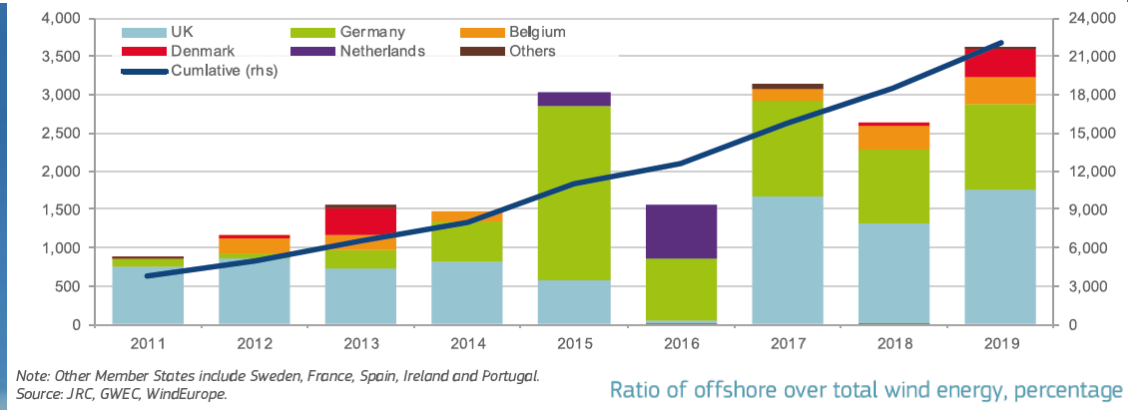



# Current «societal» challenges for civil engineering

## Green growth: promoting the growth of clean energy production

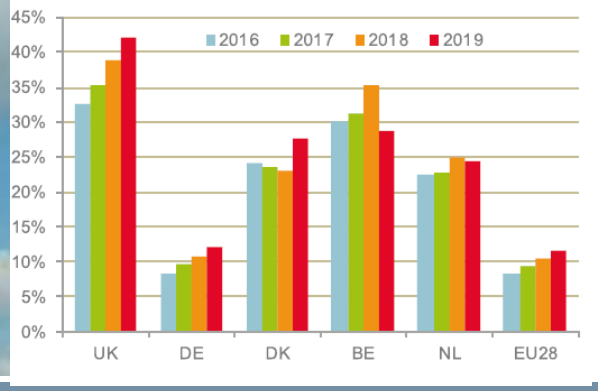
Offshore wind

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

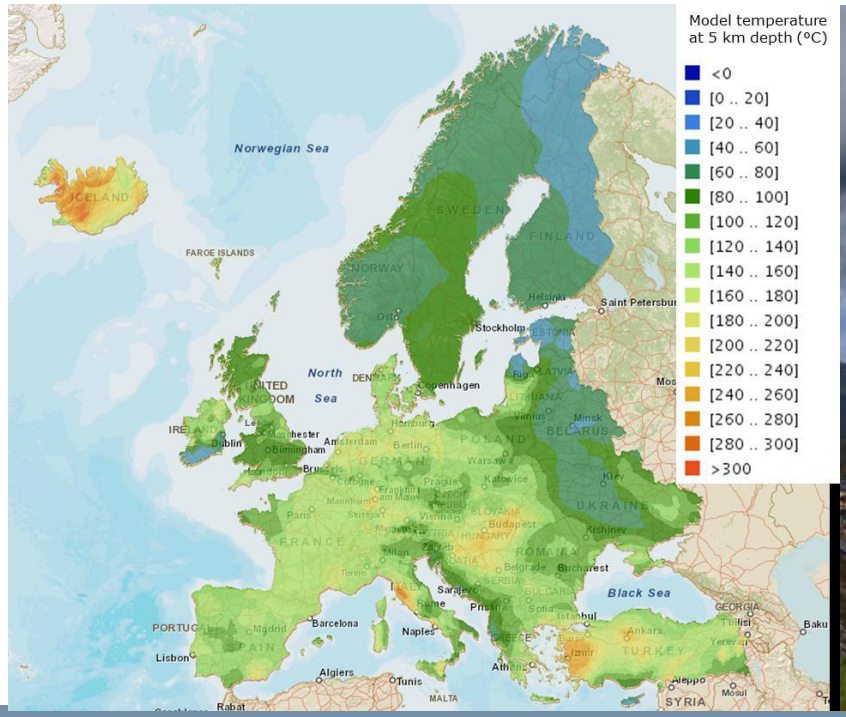


# Current «societal» challenges for civil engineering

## 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

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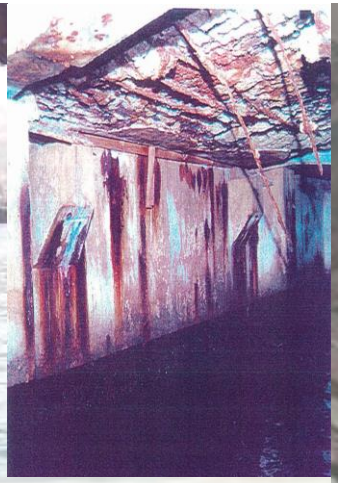


| | Maximum w/c | minimum cement content | minimum compressive strength | minimum concrete cover | maximum crack width |
|---|---|---|---|---|---|
| | | kg/m$^3$ | MPa | mm | mm |
| XS | 0.40 - 0.65 | 300 - 400 | 25 - 40/50 | 25 – 75 | 0.1 - 0.4 |
| XA | 0.45 - 0.65 | 275 | 25/30 to 40/50 | - | 0.1 -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

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

# The ReSHEALience project challenge

## The challenge

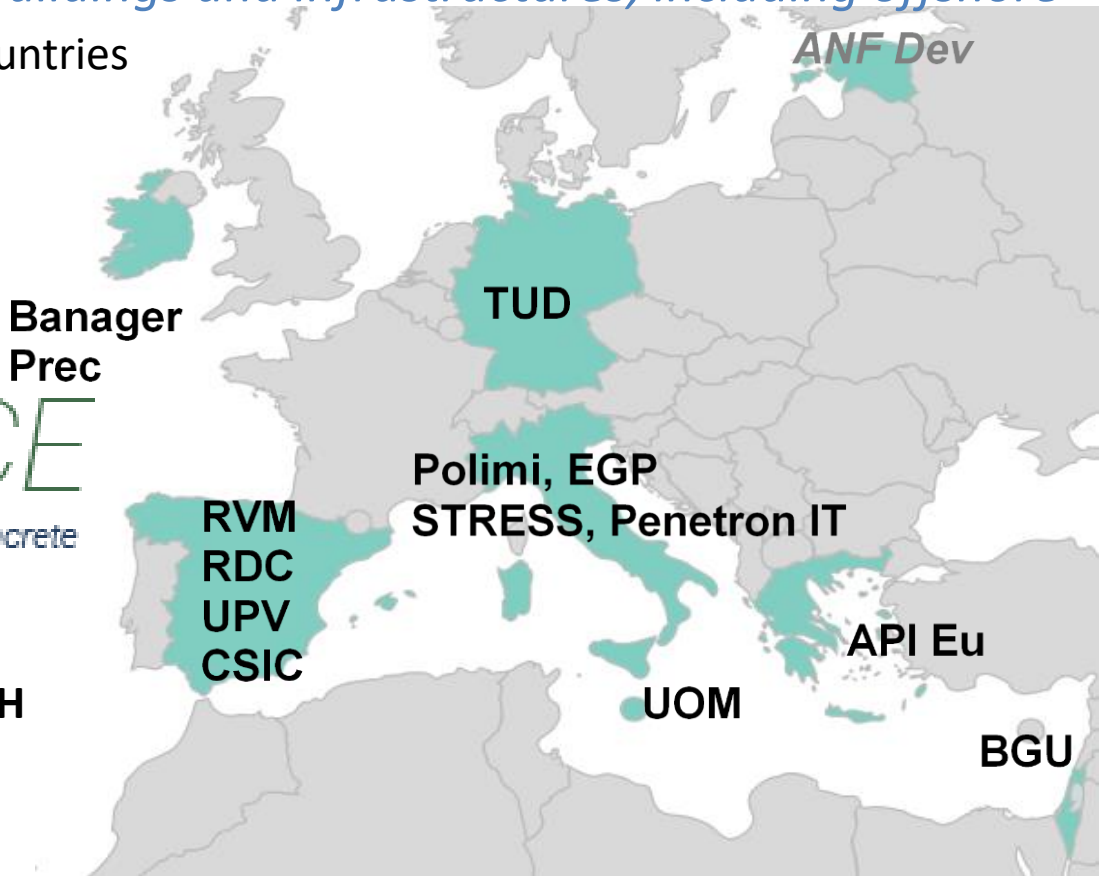
*Improved material durability in buildings and infrastructures, including offshore*

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

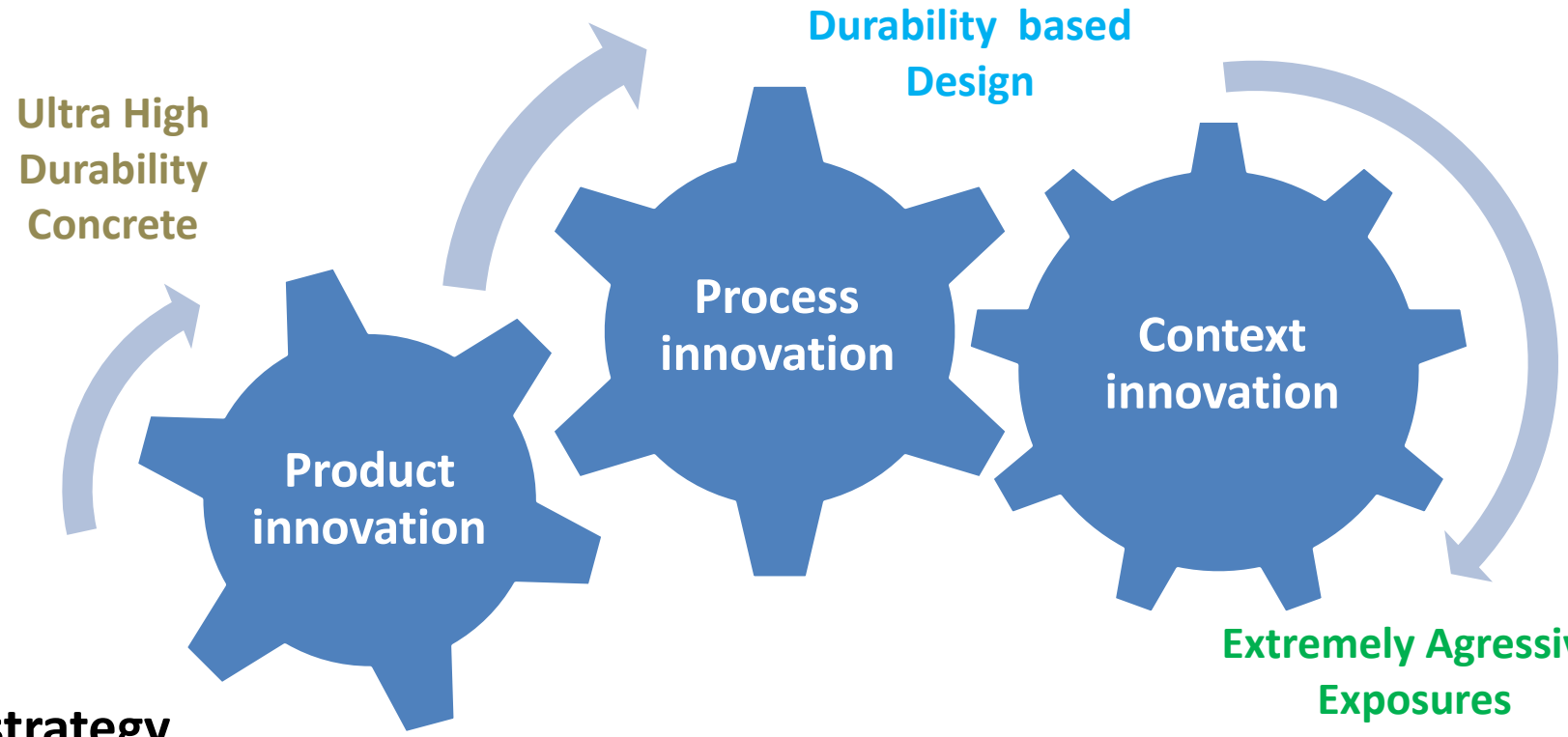
Engineering consultancy - SME

BANAGHER PRECAST CONCRETE

RDC

Precast concrete construction and engineering consultancy - SME

# The 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: durability of UHPC in cracked state

**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".*

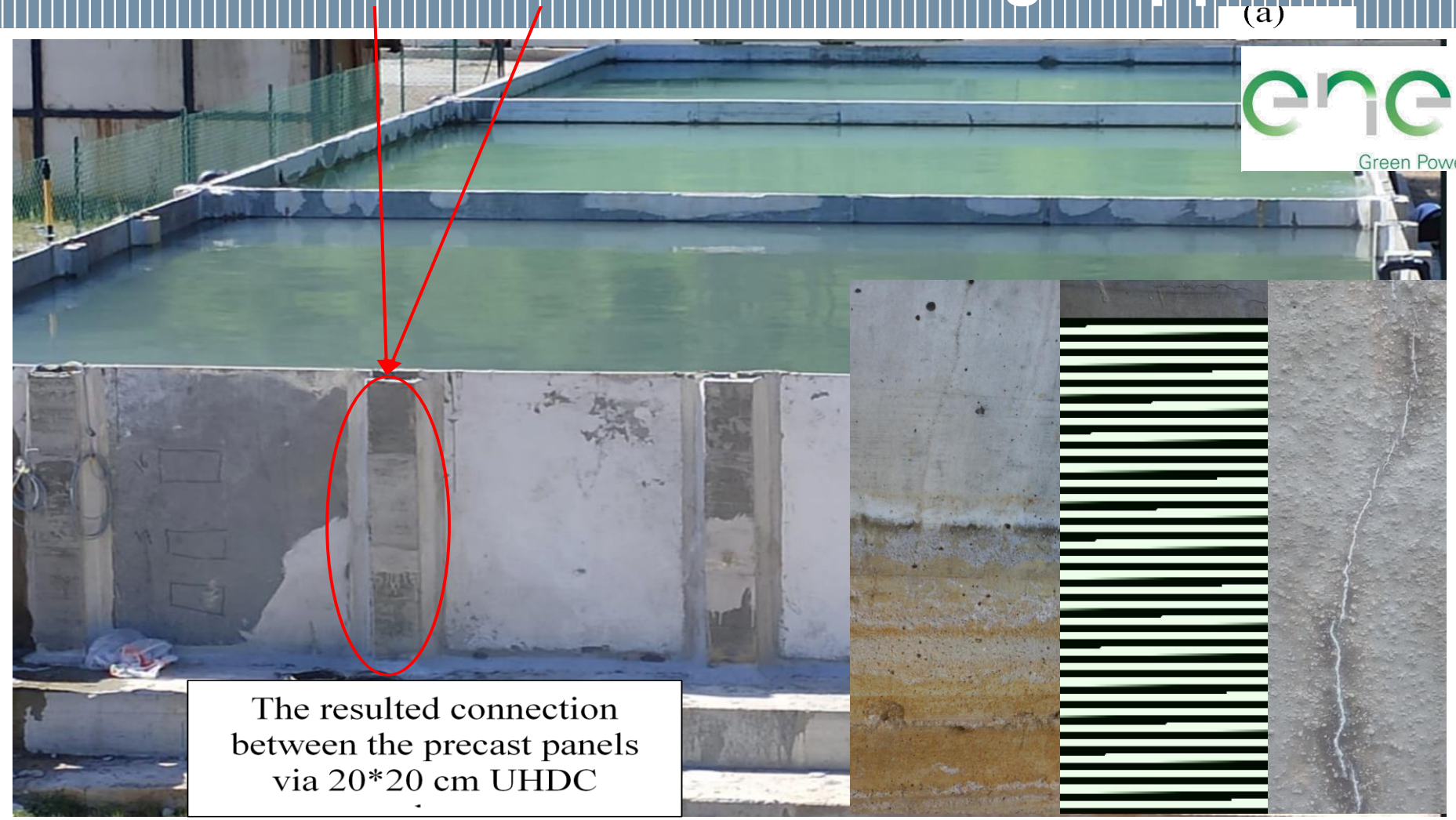
*"if you replace concrete/cement-based materials with any other construction material … it will have a bigger CO2 footprint!".*

# The ReSHEALience project strategy: 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

## 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

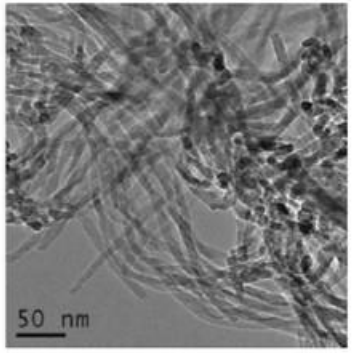
NAFEN
Enhancing the world with nano

PENETRON

APiEurope

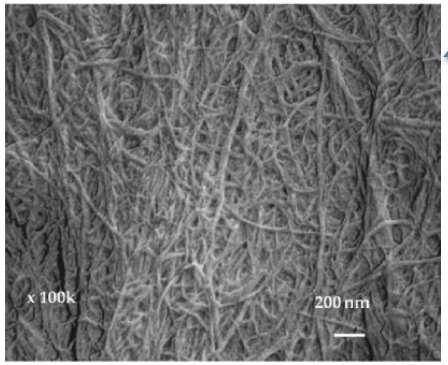
## Alumina nanofibres

| | |
|---|---|
| Nanofibers content (by weight) [ISO 3251] | 10% |
| Particle size [SEM] | Diameter: 4-11 nm<br>Length: 100-900 nm |
| Surface area [BET] | 155 $m^2/g$ |
| Dispersion basis | Deionized Water |
| pH [ASTM D1293] | 6.4 – 7.8 |




## Crystalline admixture

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




## 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 |

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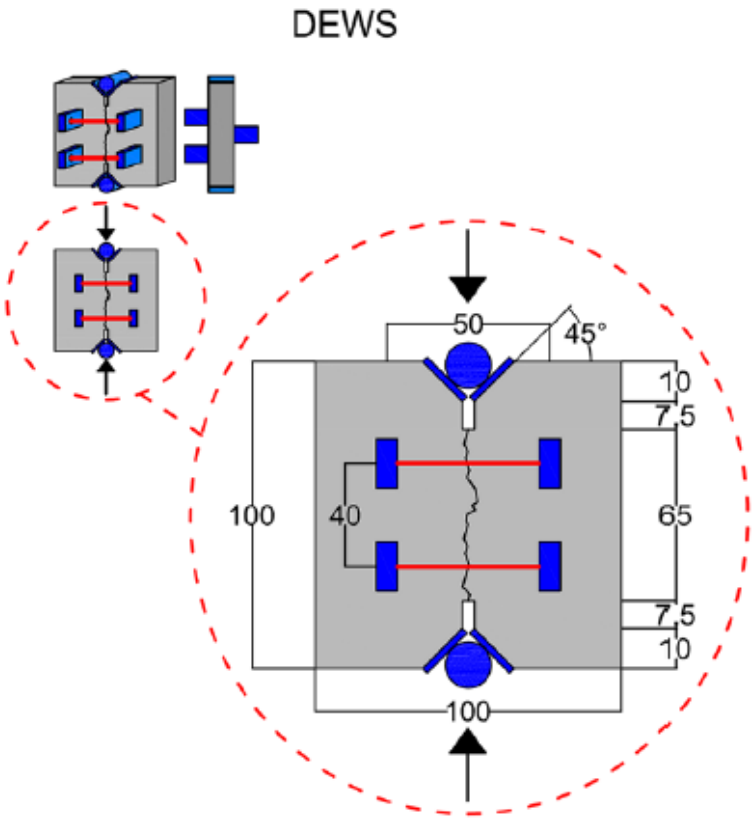


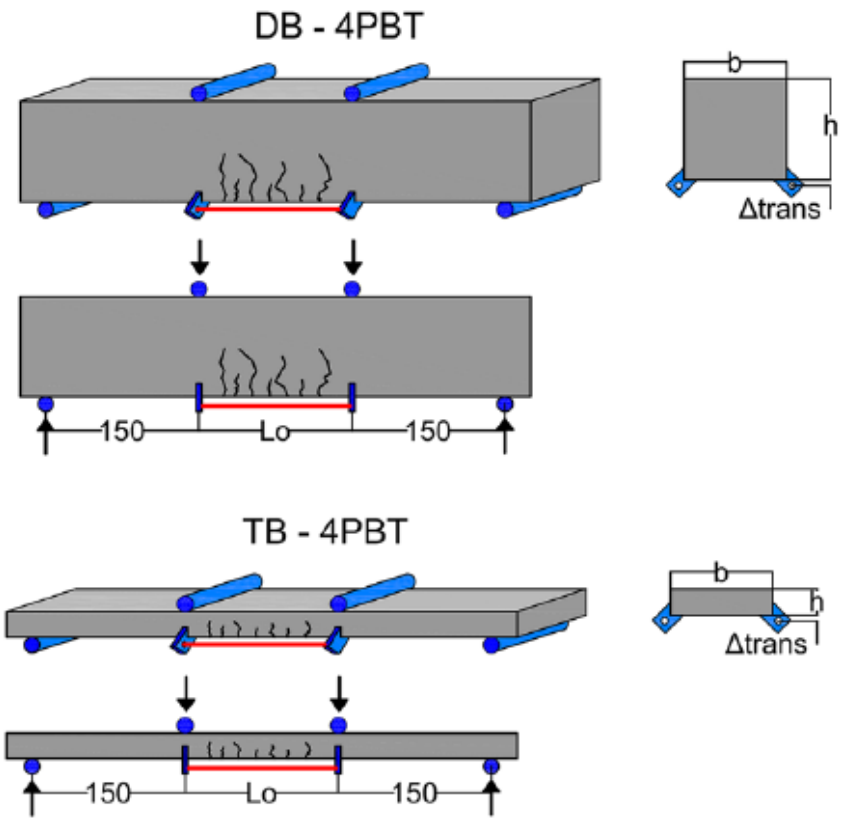

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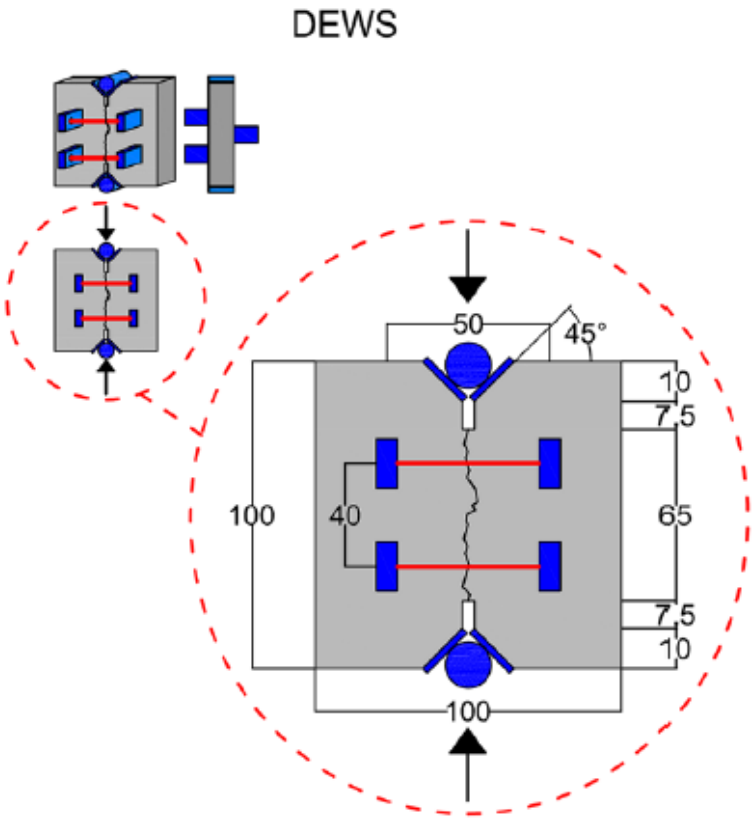


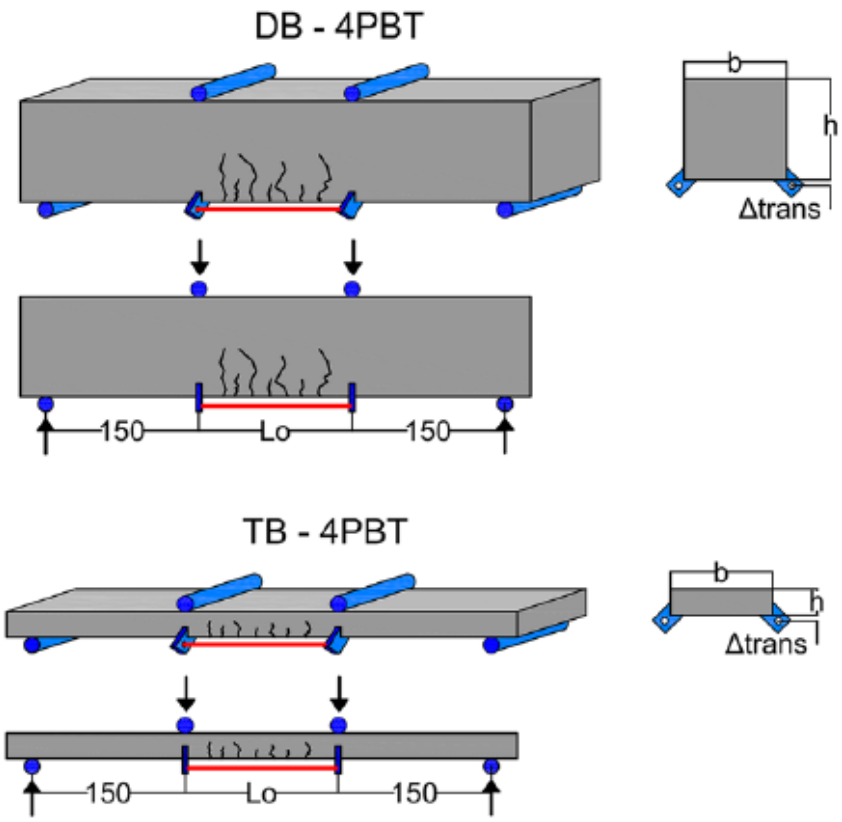

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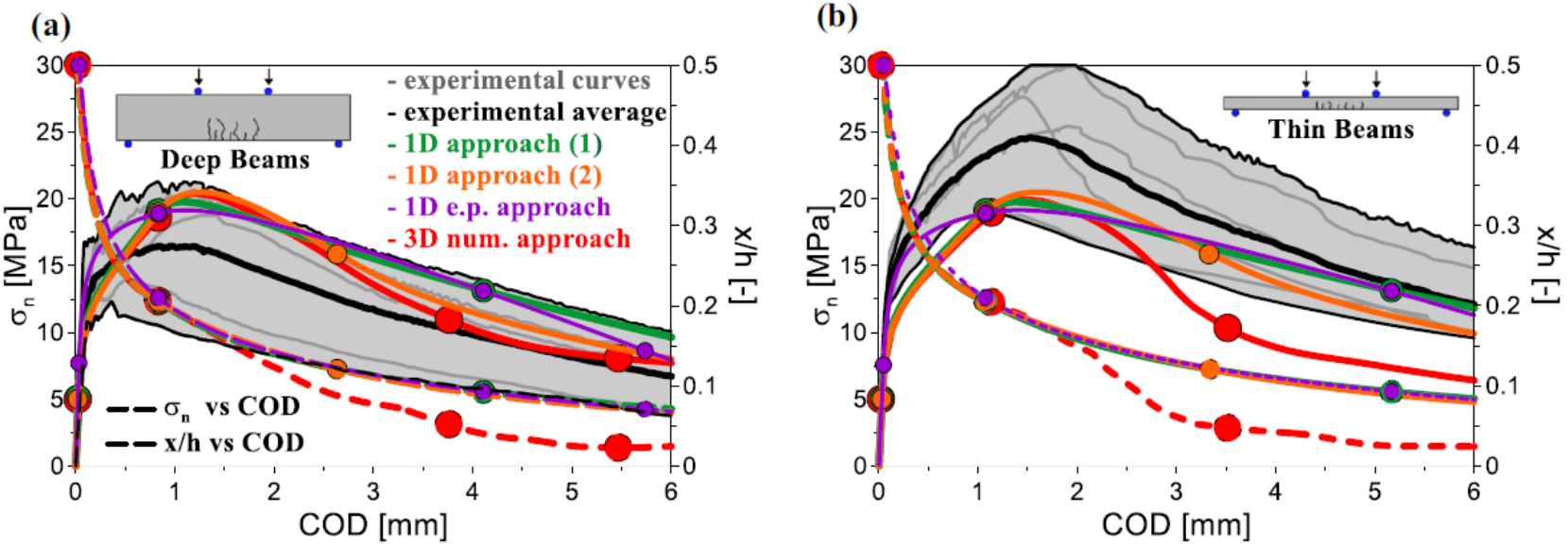


| MIX ID | Min/average/Max n° of cracks | Average crack spacing (mm) |
|---|---|---|
| Reference | 2/7/12 | 30 |
| Alumina nanofibres | 9/12/15 | 17 |
| Cellulose nanofibrils/crystals | 6/7/9 | 21 |

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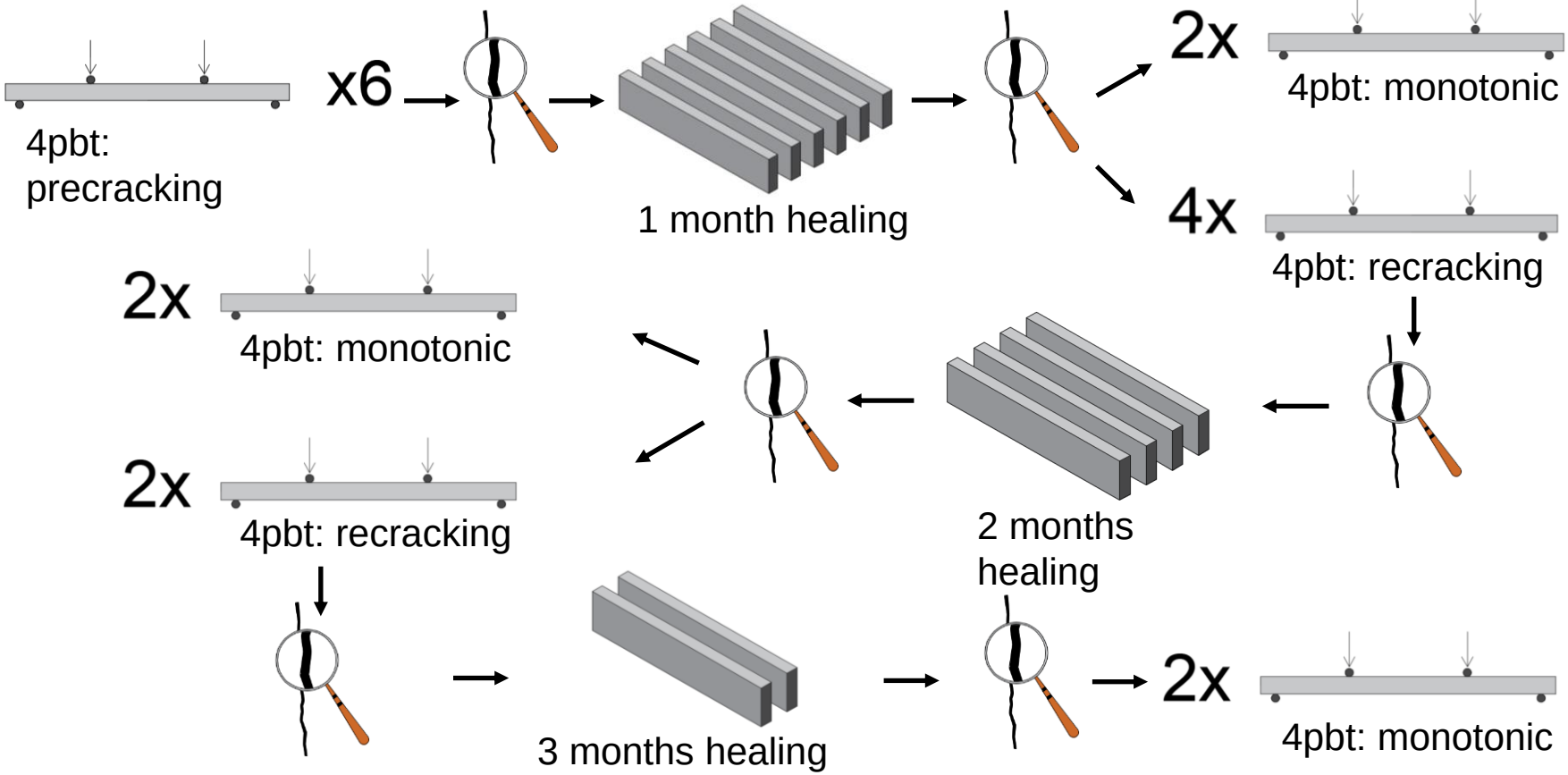


$$\text{Index of Crack Sealing ICS} = 1 - \frac{A_{crack,t}}{A_{crack,0}}$$

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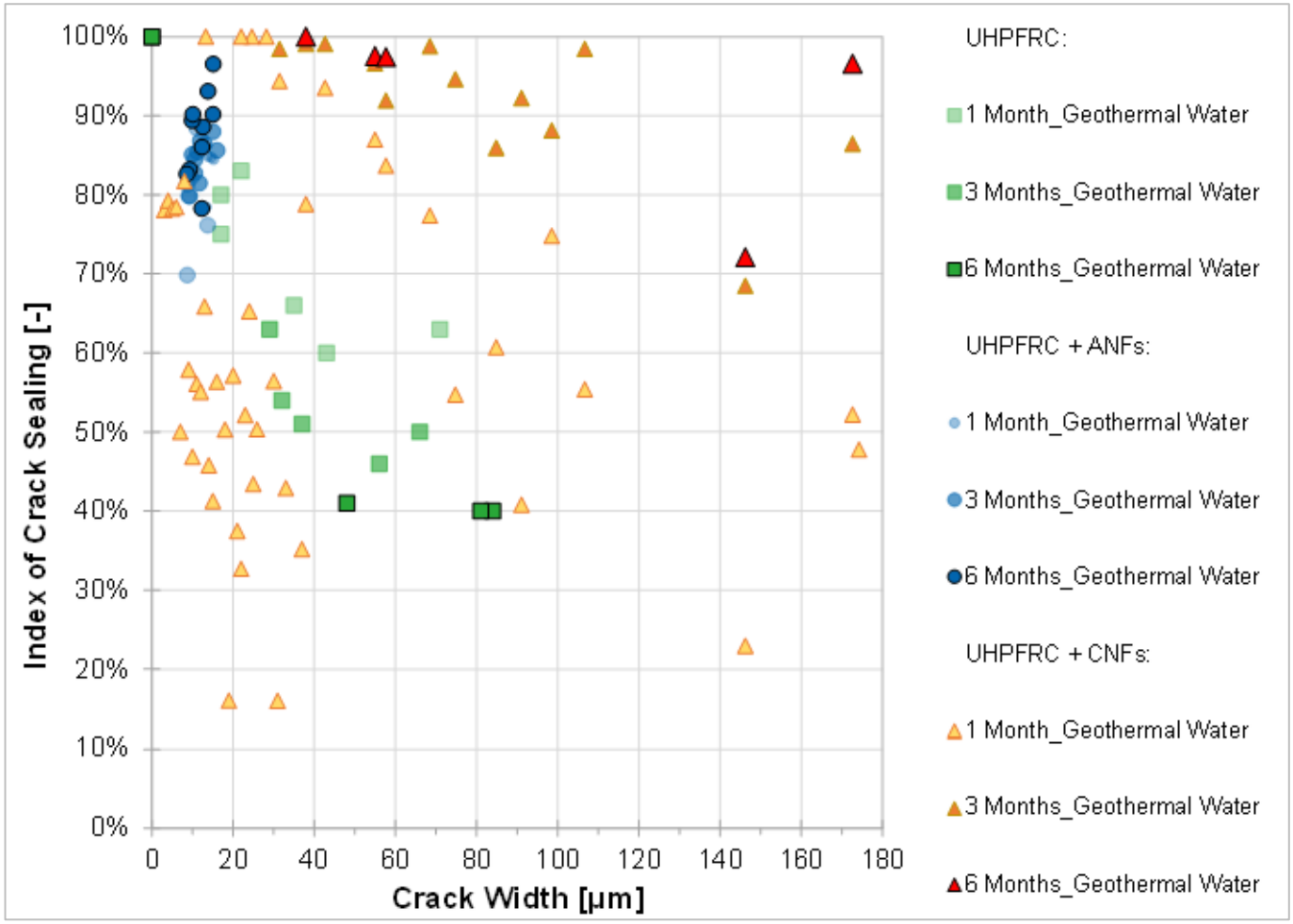


Cuenca et al.
CBM 2021
CCC 2022
Materials 2022
CBM 2023

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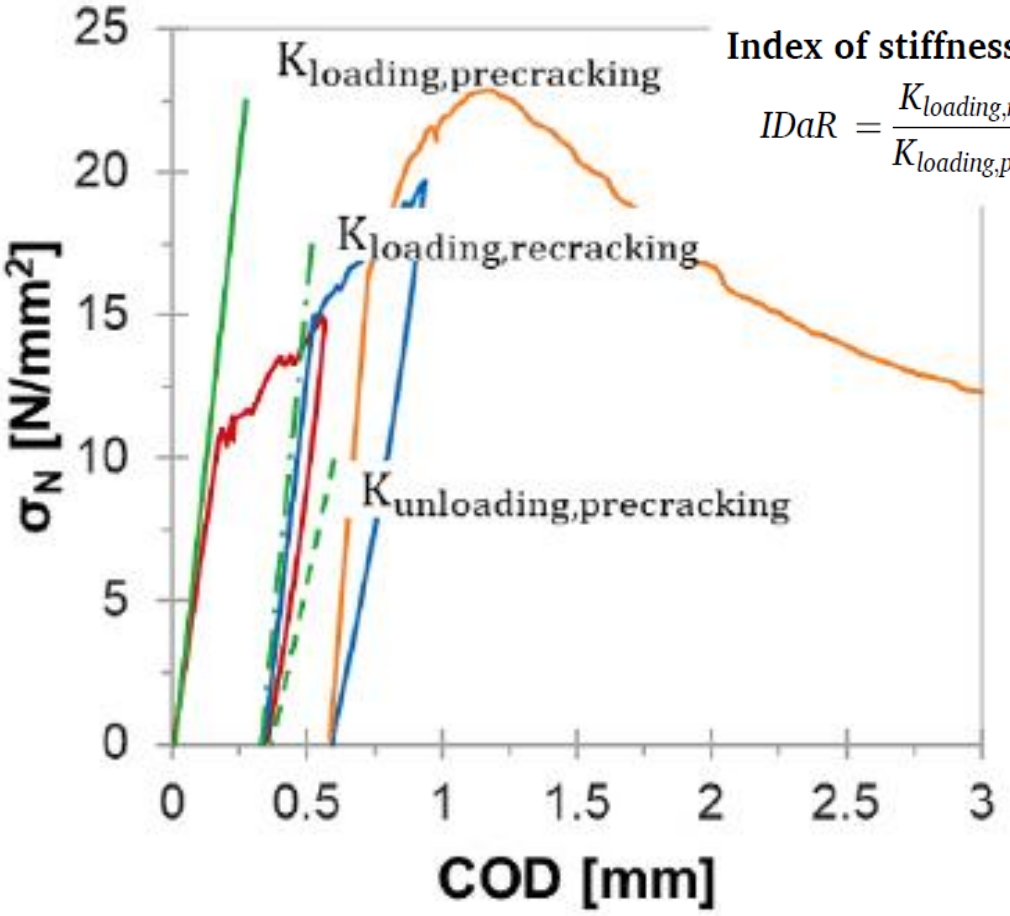
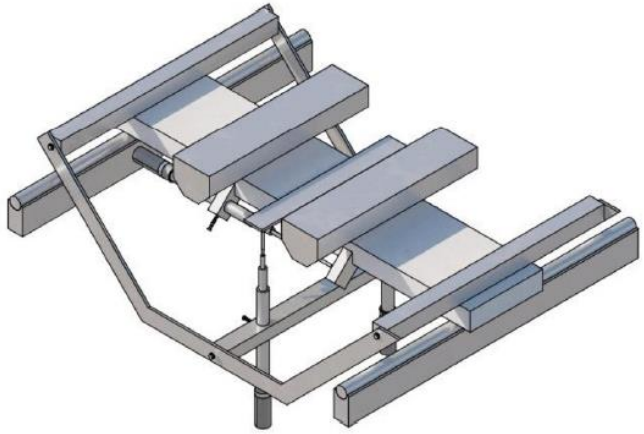



**Index of stiffness/Damage Recovery (IDaR)**

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



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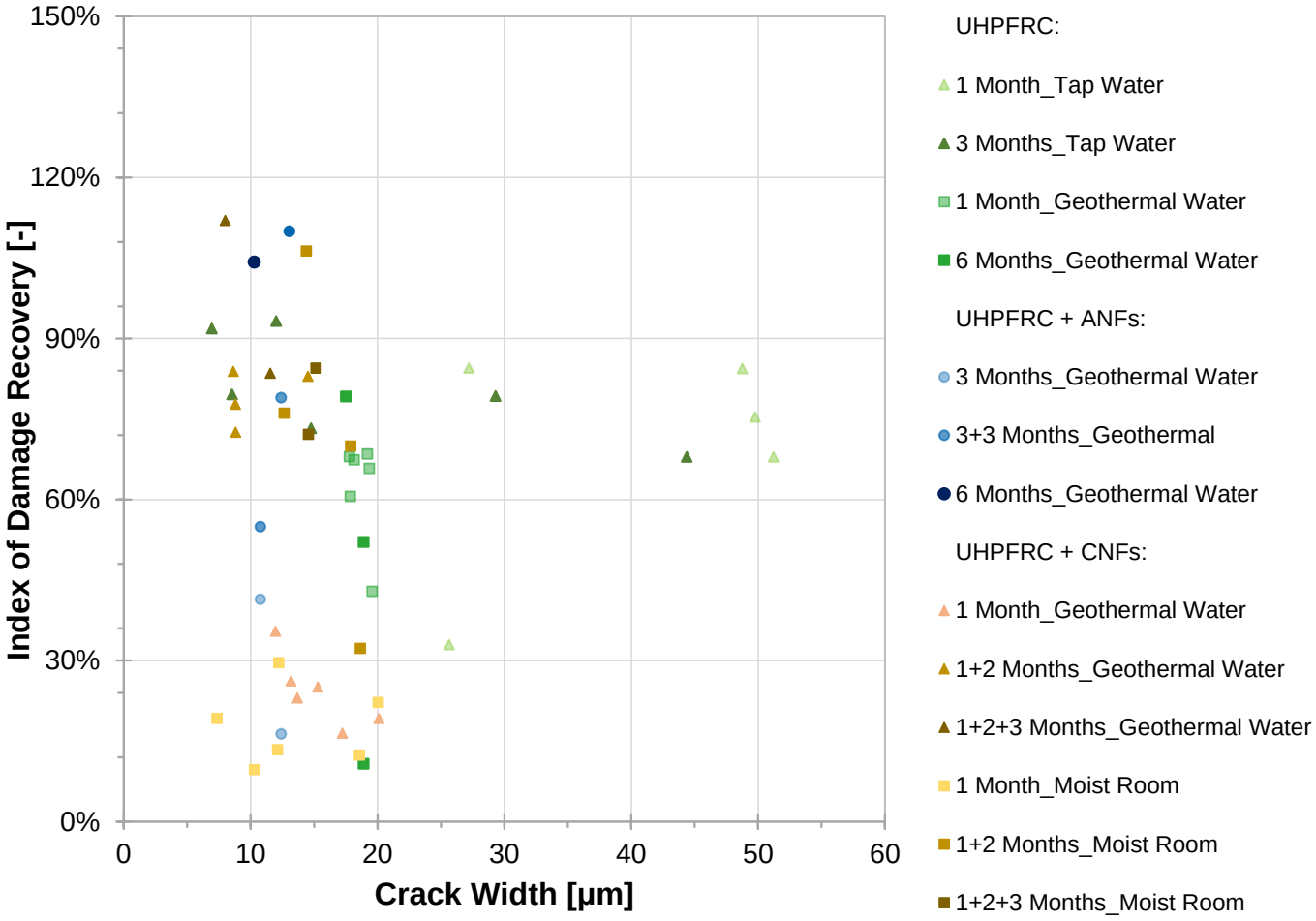


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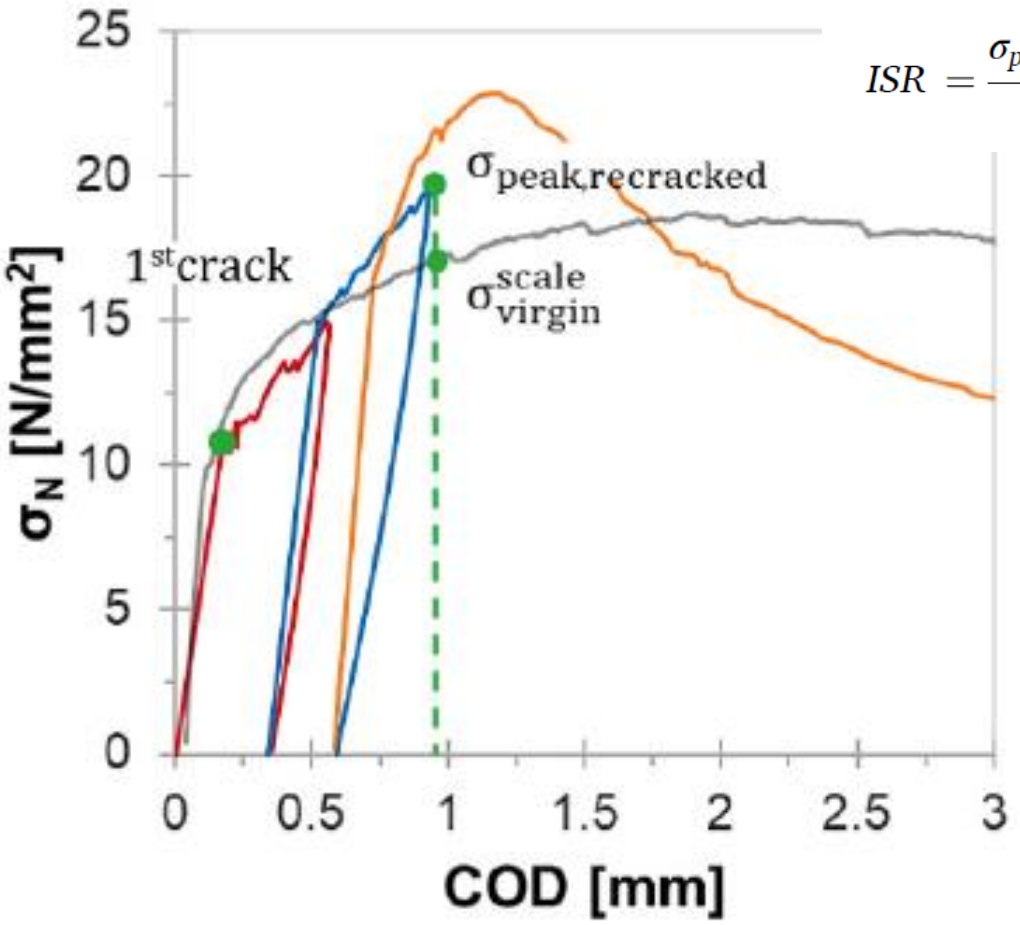


**Index of Stress Capacity Recovery (ISR)**

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

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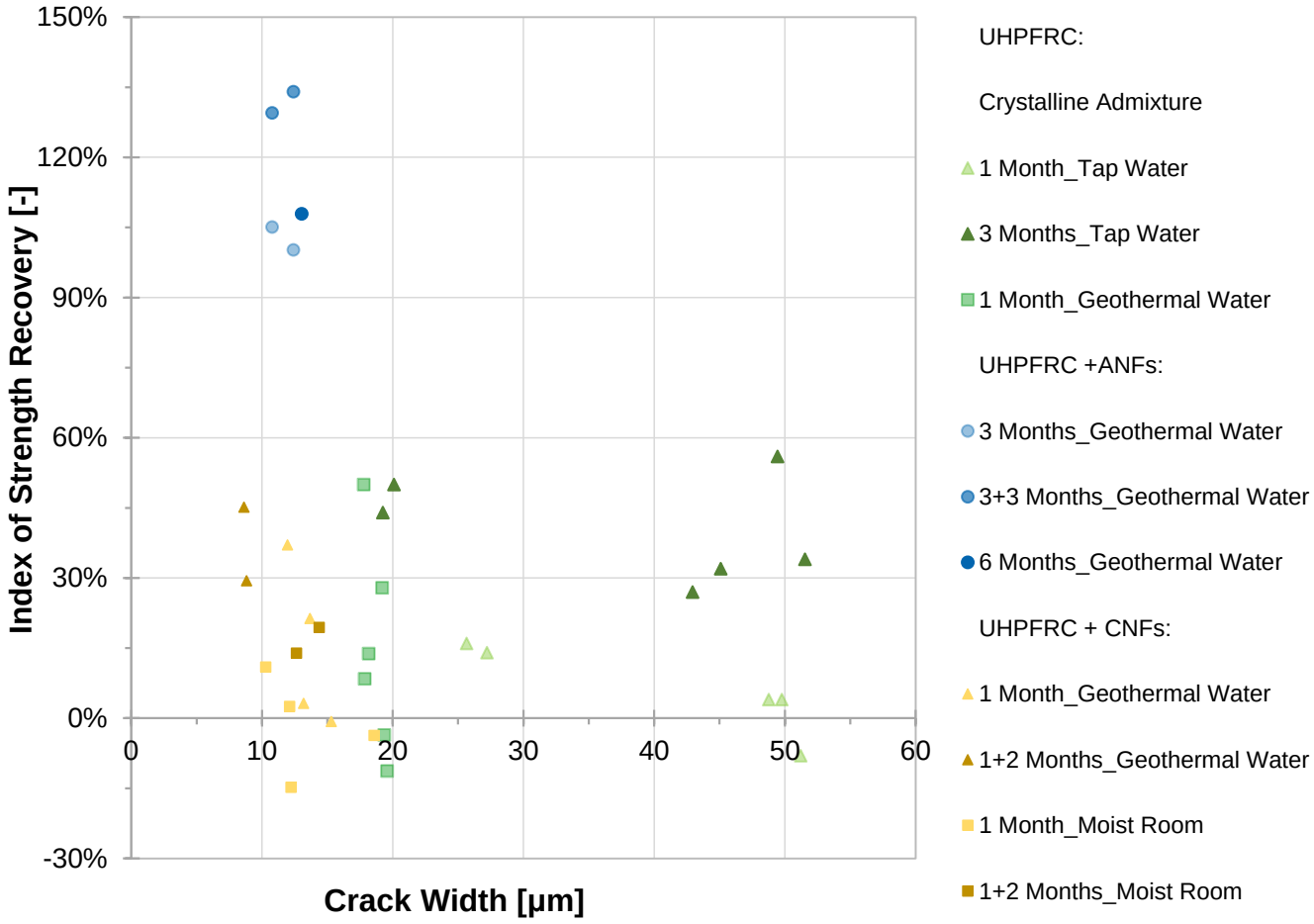


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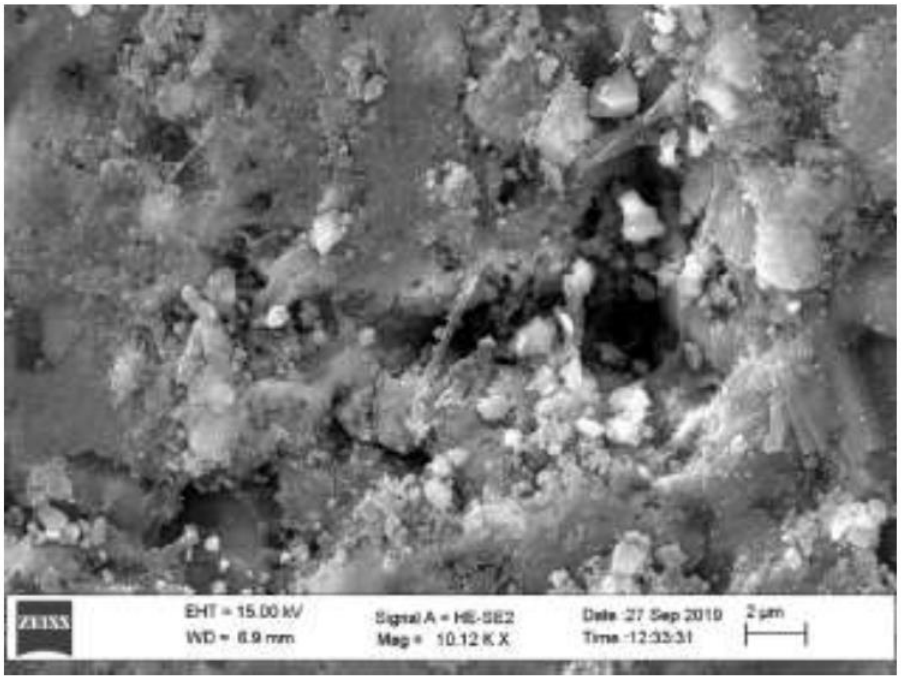
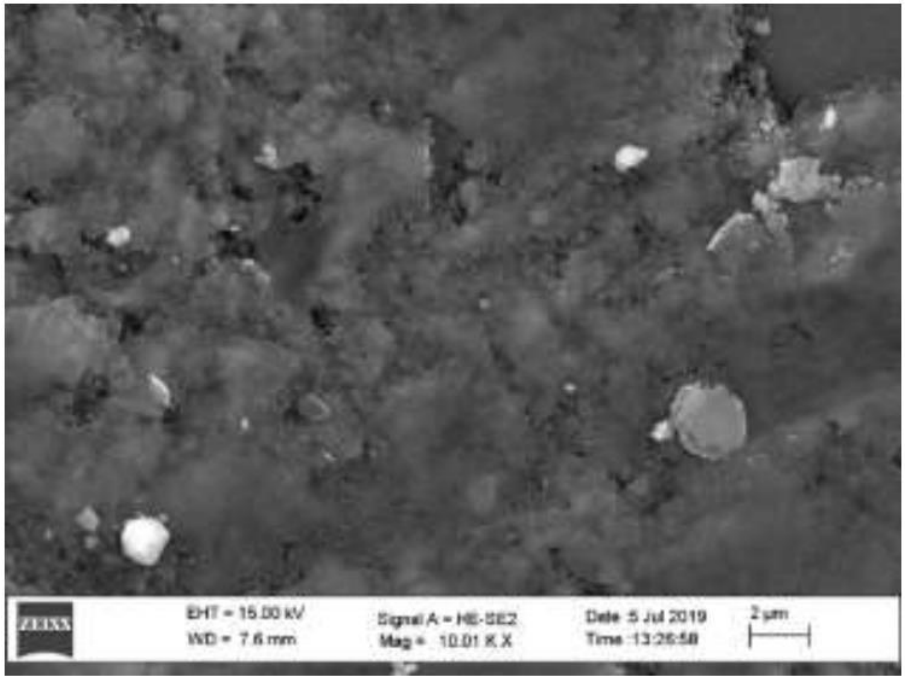
# The ReSHEALience project strategy: towards a novel holistic design approach

With/without alumina nanofibres – curing in moist room

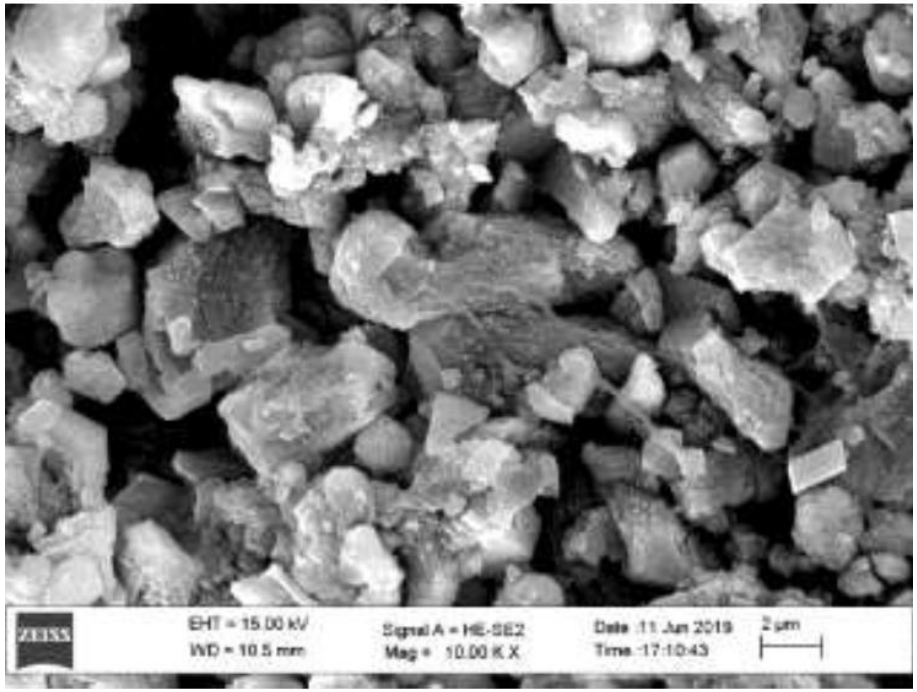


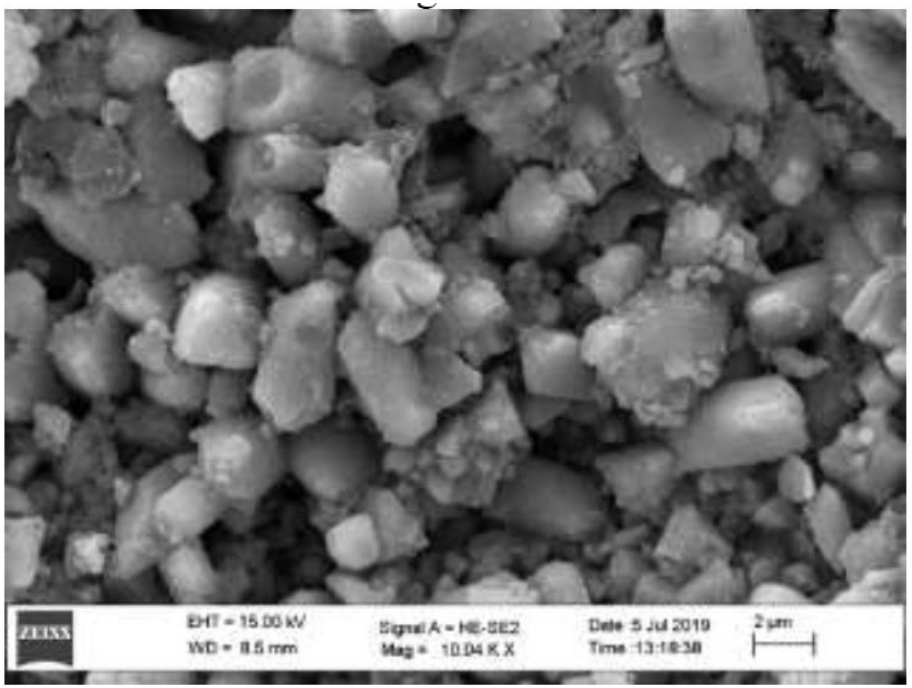




Cuenca et al., CCC 2022

# The ReSHEALience project strategy: towards a novel holistic design approach

With/without alumina nanofibres – curing in geothermal water

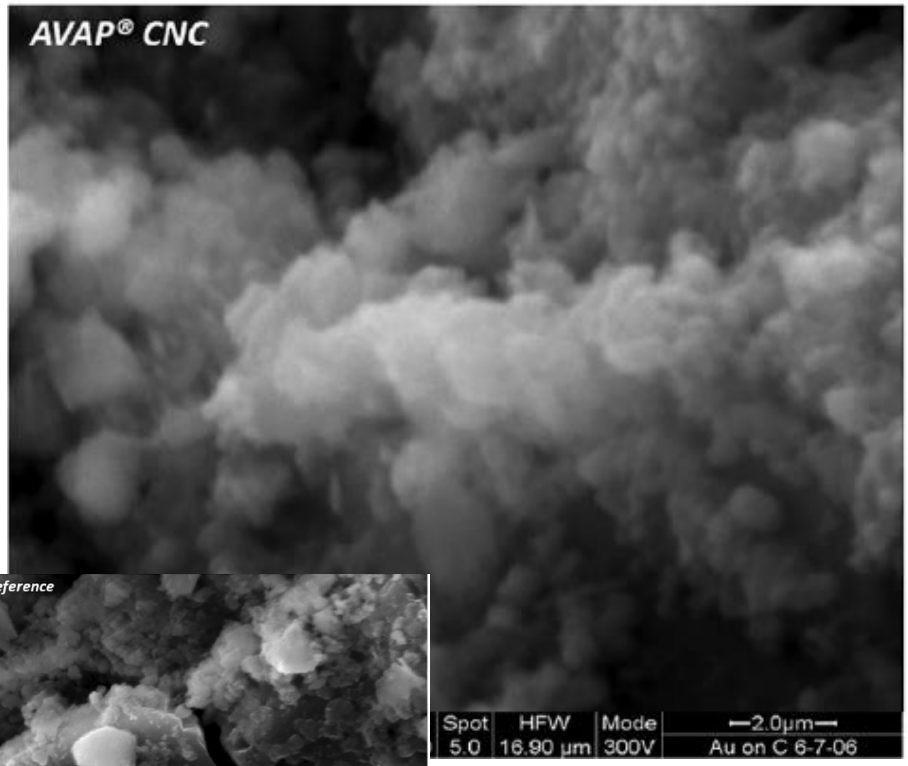


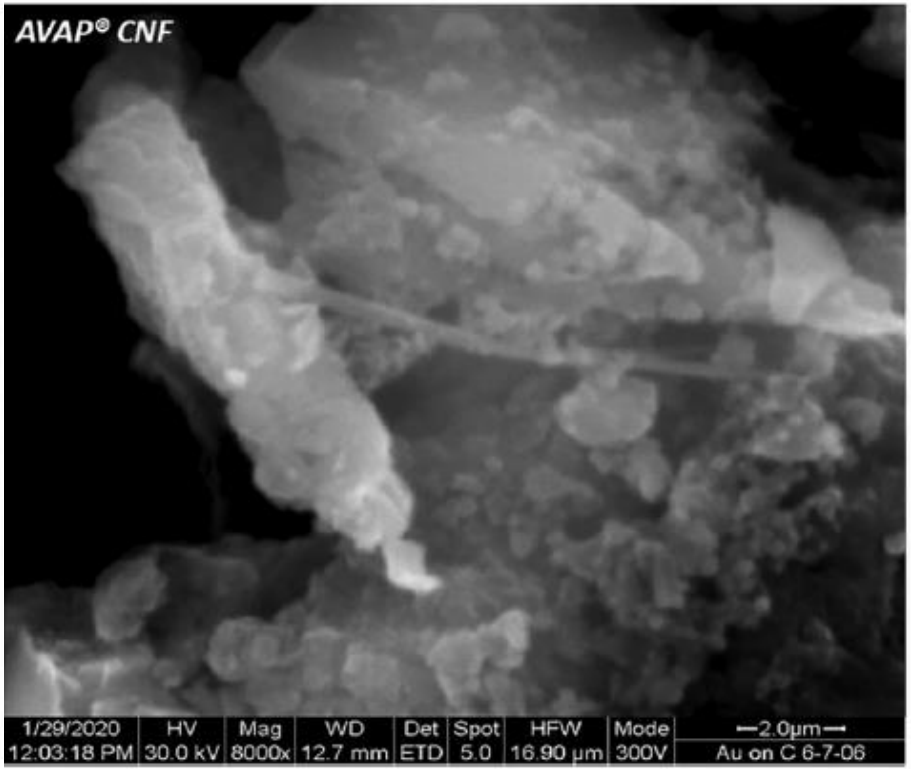



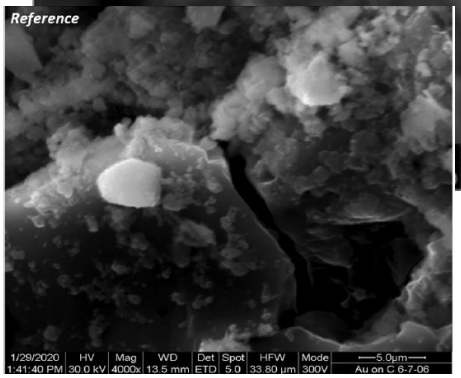

Cuenca et al., CCC 2022

# The ReSHEALience project strategy: towards a novel holistic design approach

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



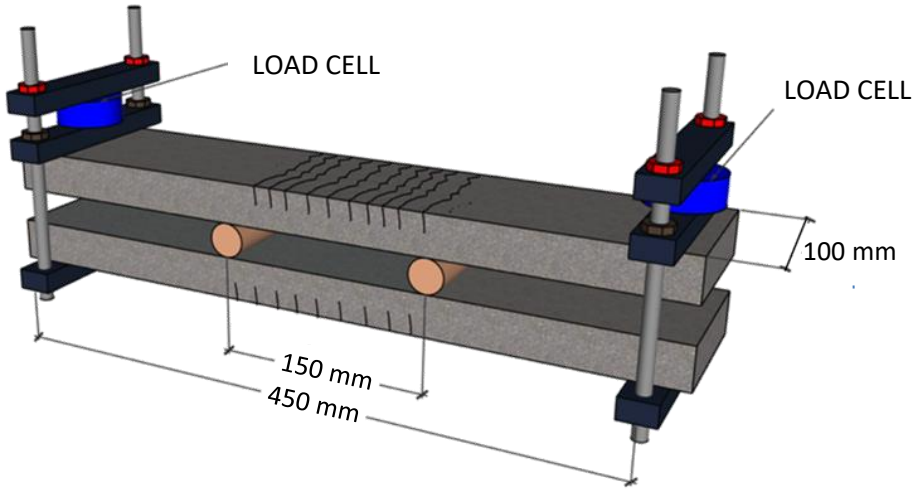



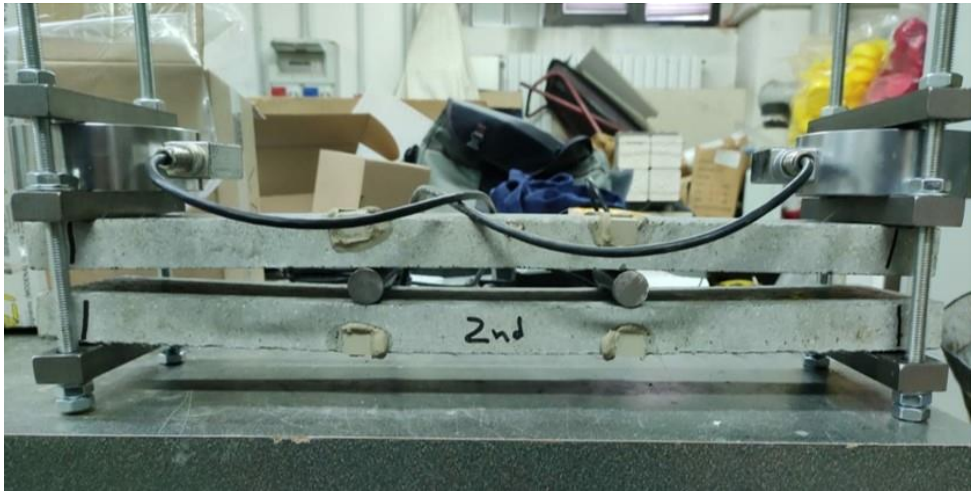

Deze et al., Materials Today 2022

# The ReSHEALience project strategy: towards a novel holistic design approach

## Design for durability

Identify the real «in structure» material behaviour




Davolio et al., CCC 2023

# The ReSHEALience project strategy: towards a novel holistic design approach

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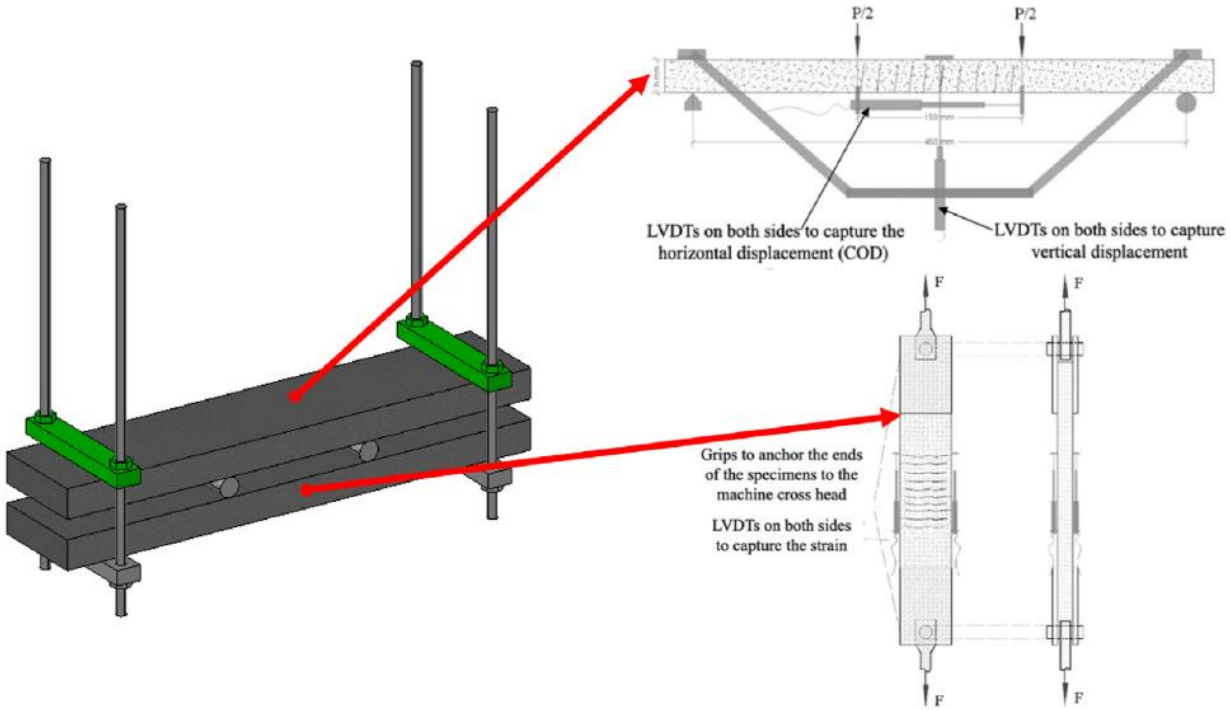


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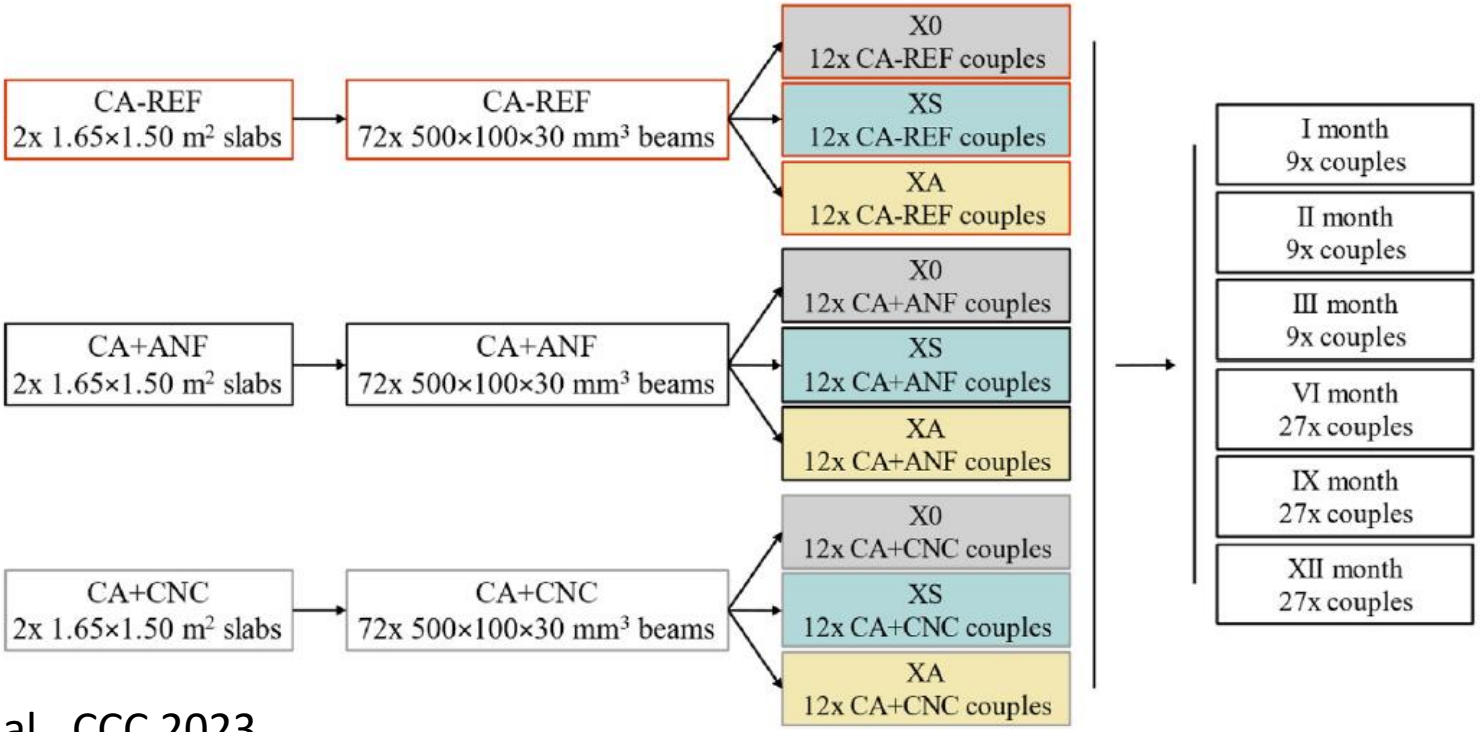


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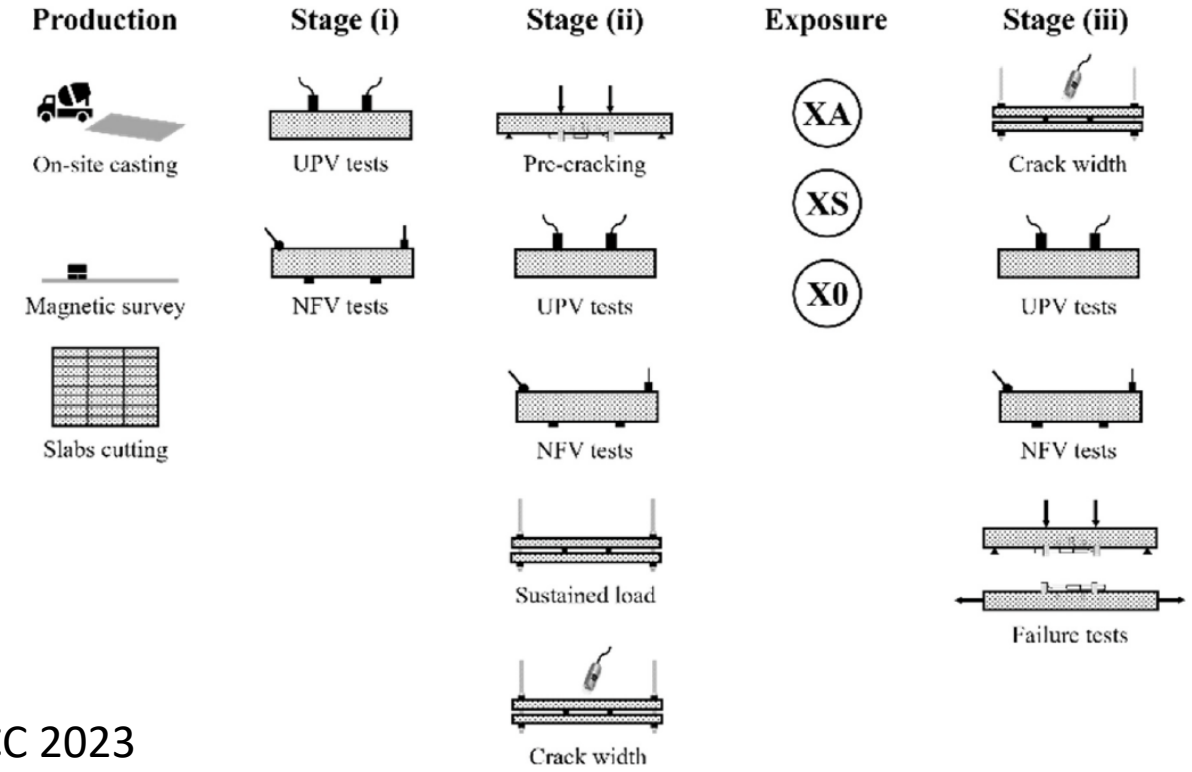


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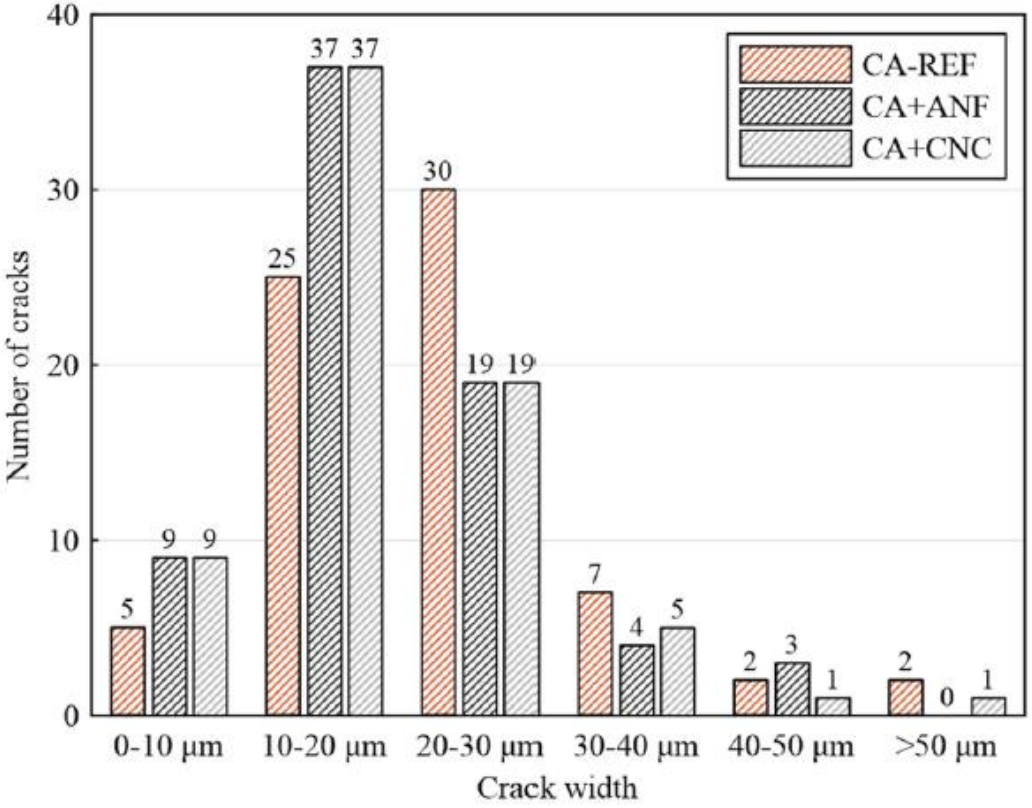


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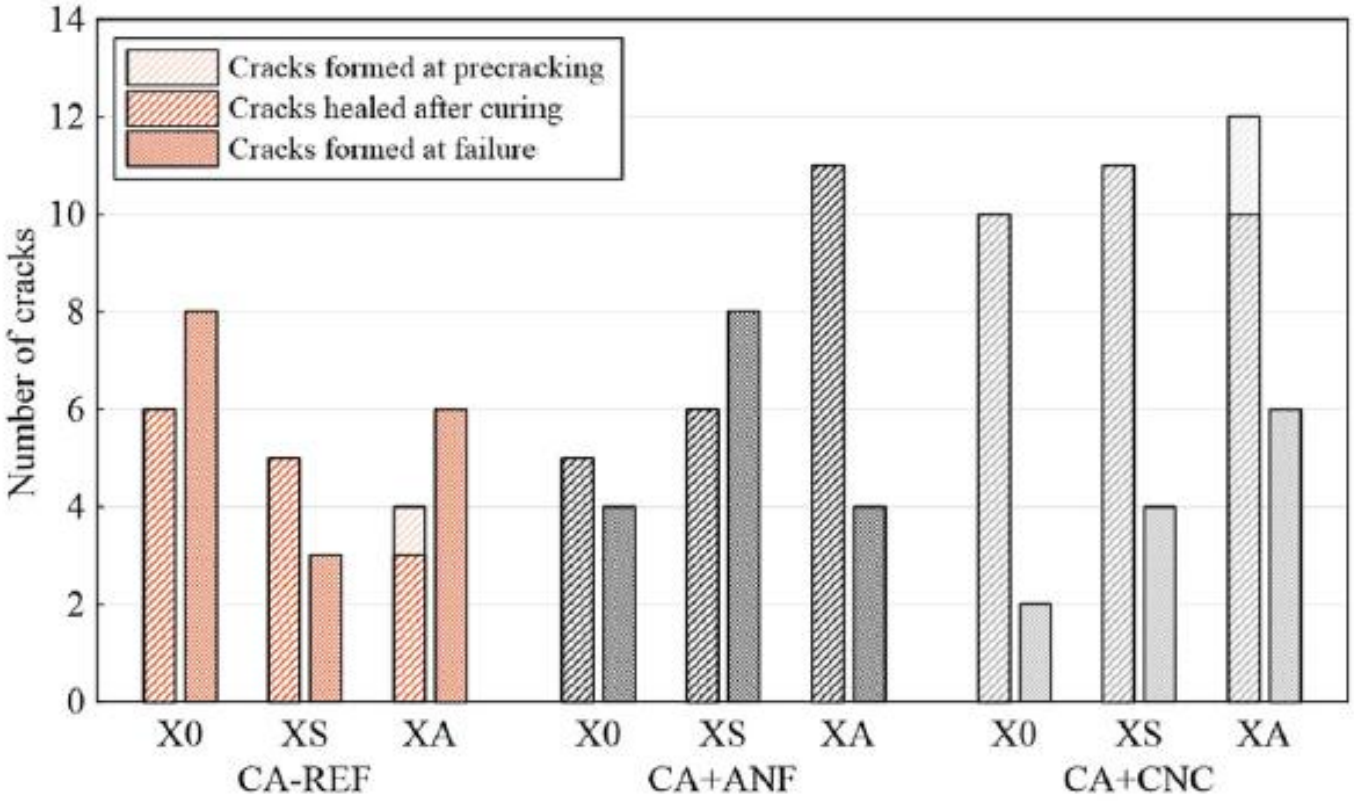


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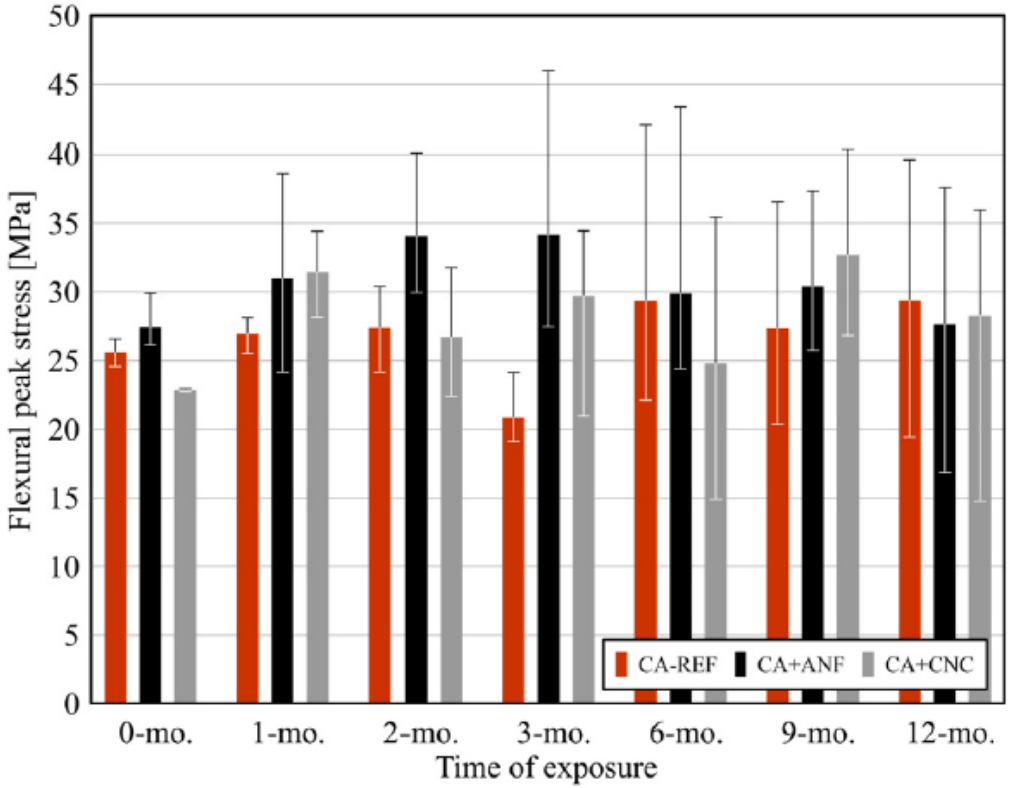
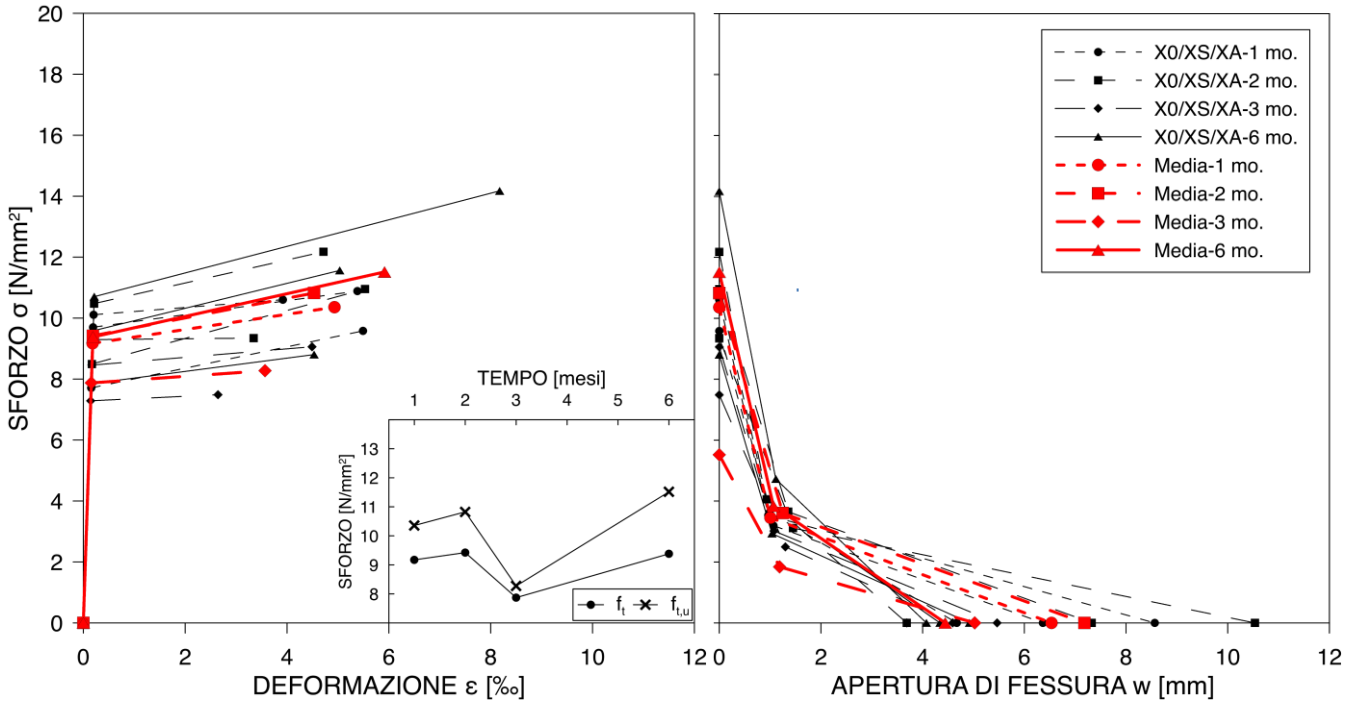



Davolio et al., CCC 2023

# The ReSHEALience project 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

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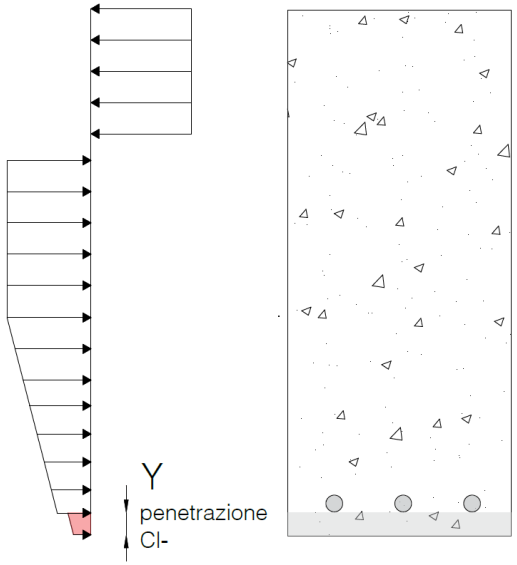
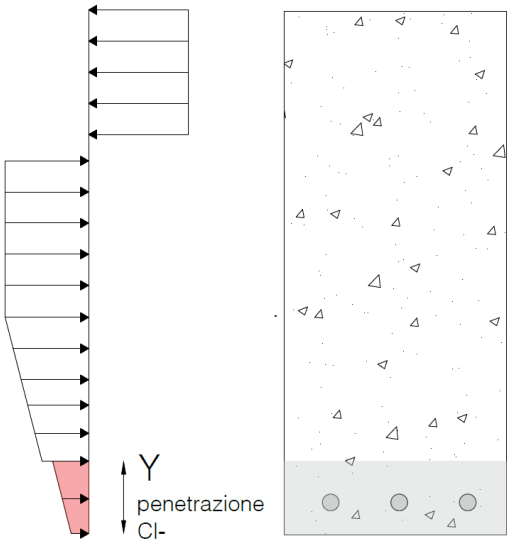
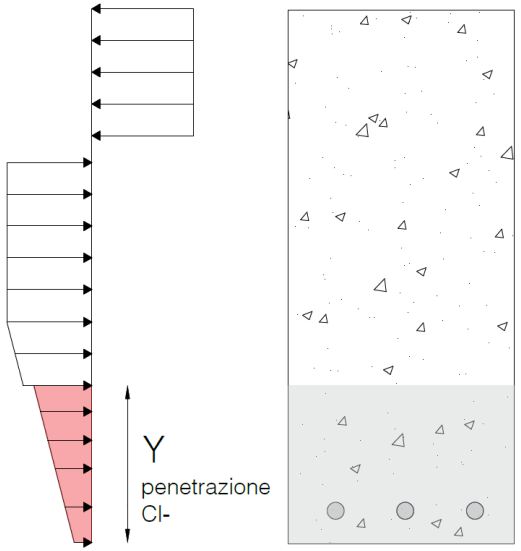


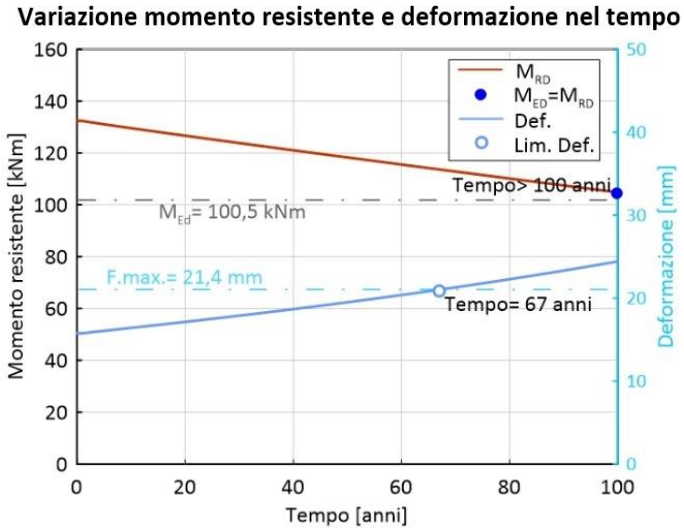

Soave et al., in preparation

# The ReSHEALience project strategy: towards a novel holistic design approach

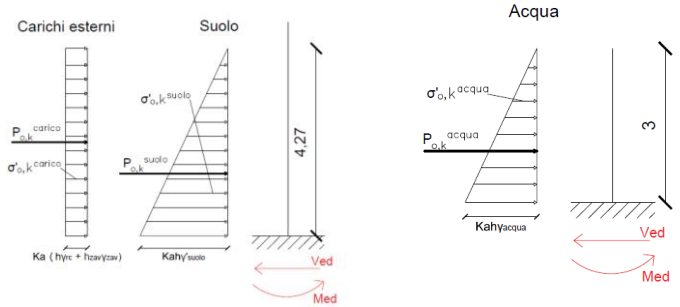
## Design for durability

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

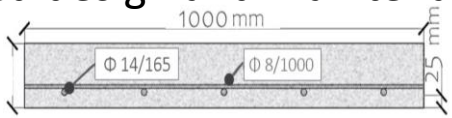
How do we evaluate $M_{Rd}(t)$? – sulphate attack




no maintenance in 50 years?




Shift from ULS governed design
to SLS governed design and maintenance planning

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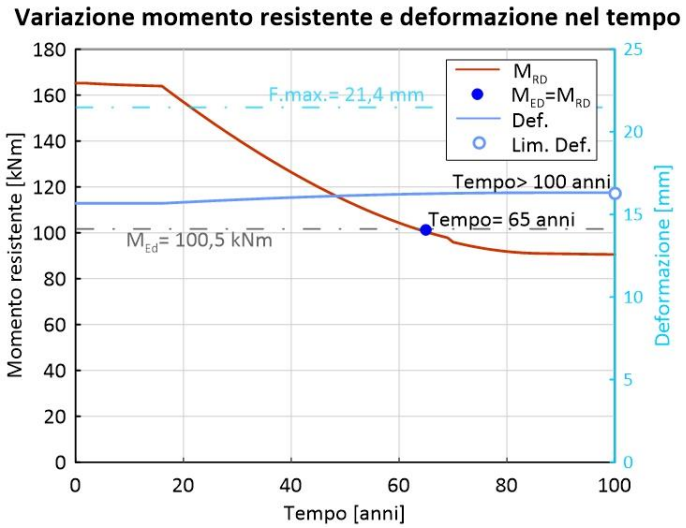


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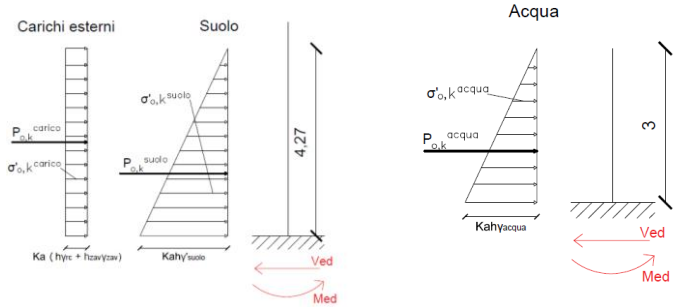


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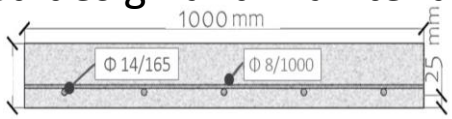


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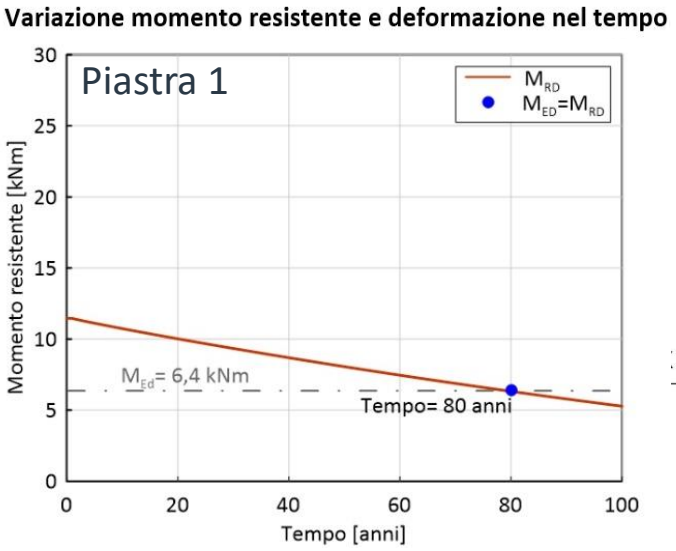


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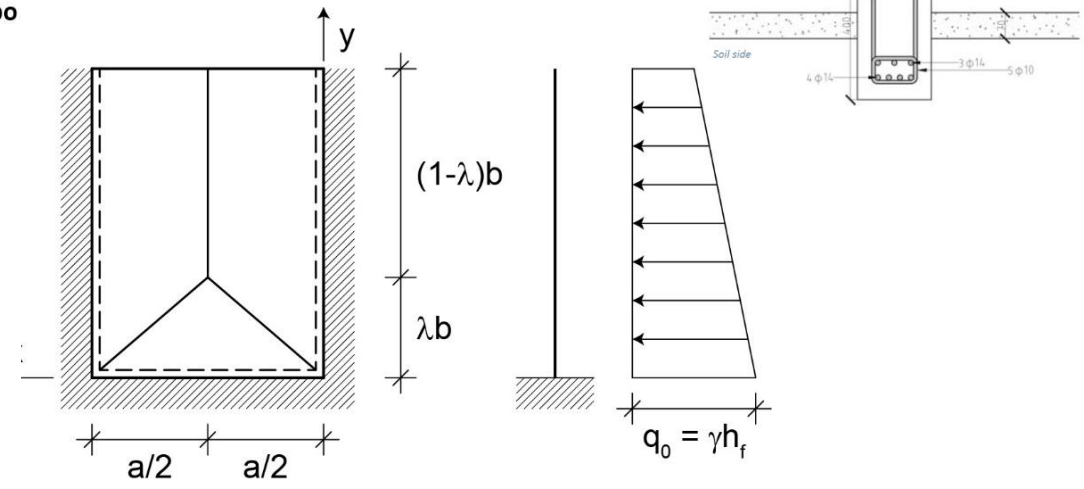
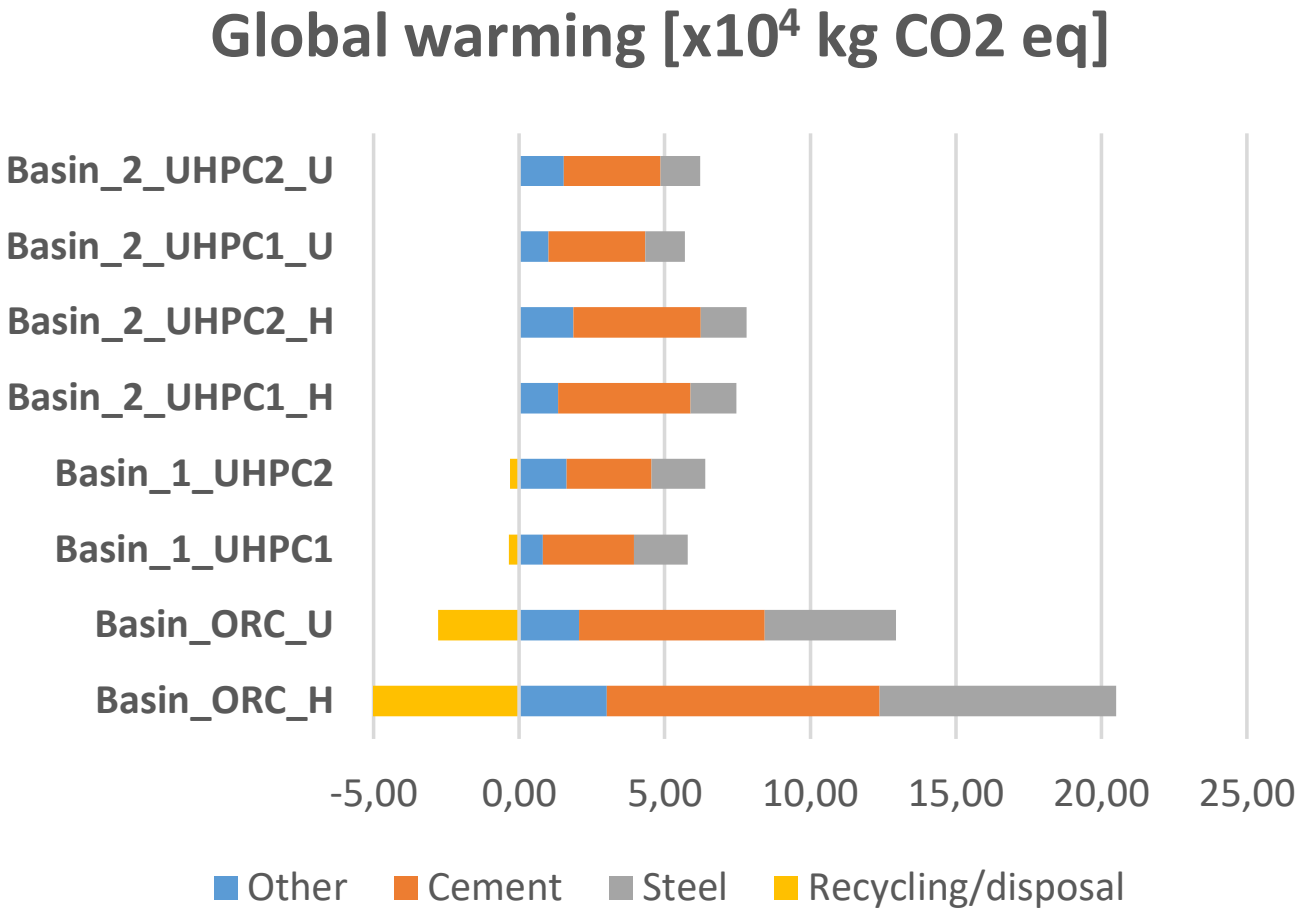



di Summa et al., Structural Concrete 2023, submitted

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

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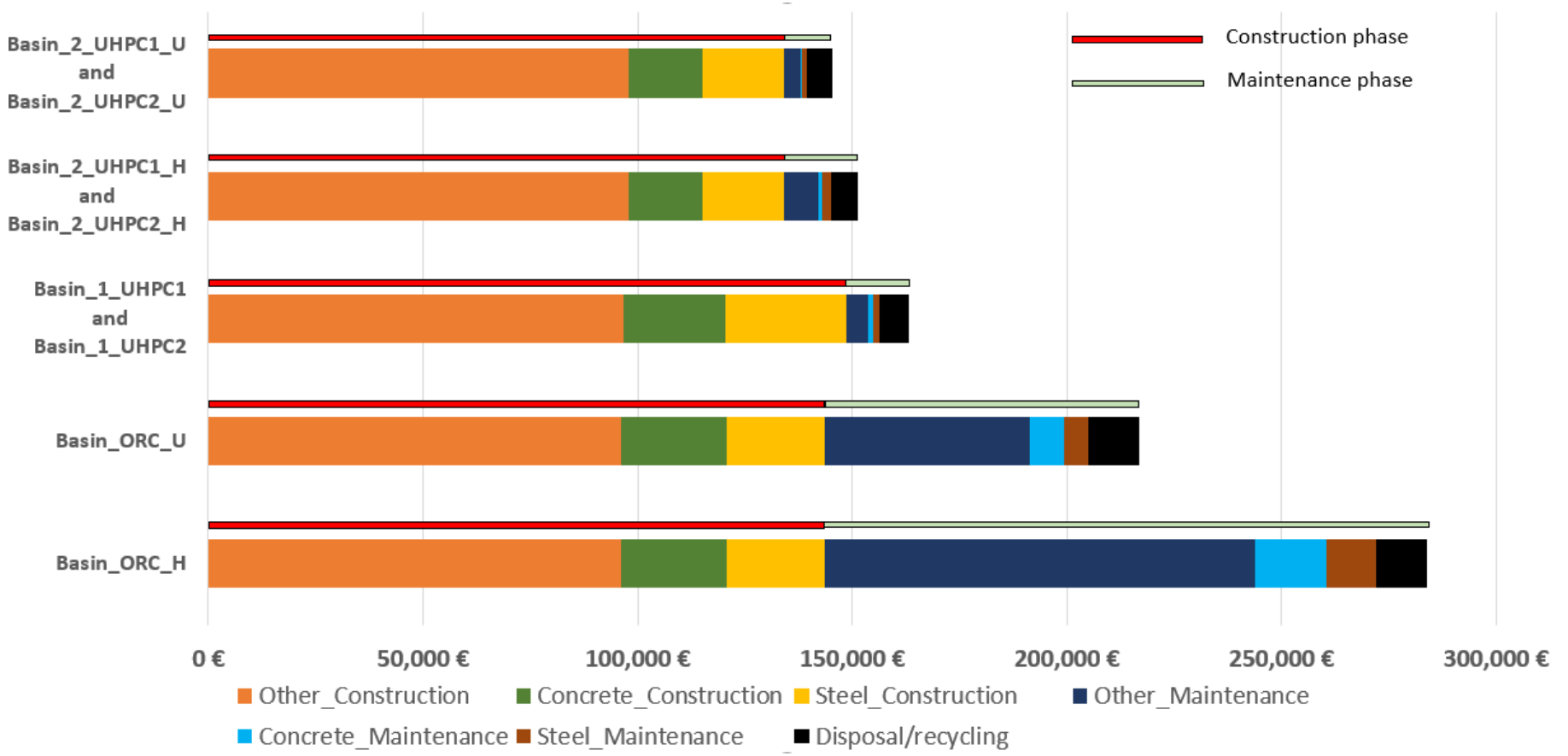


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# Concluding remarks

## «nanofunctionalized UHPC»

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

Liberato Ferrara, Department of Civil and Environmental Engineering

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# … 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

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