A new mix design methodology for recycled aggregate concrete by combining experimental/numerical approaches

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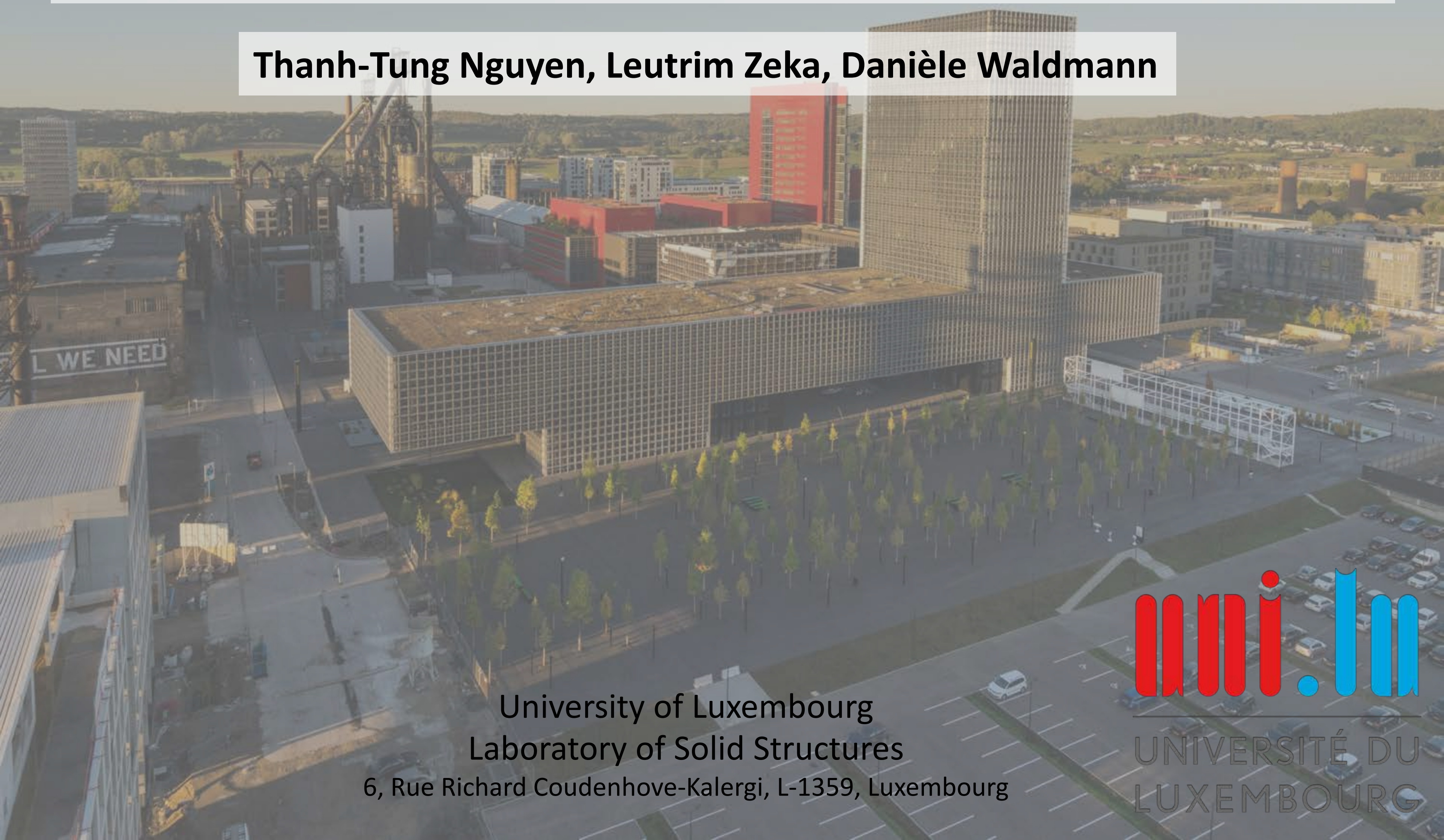

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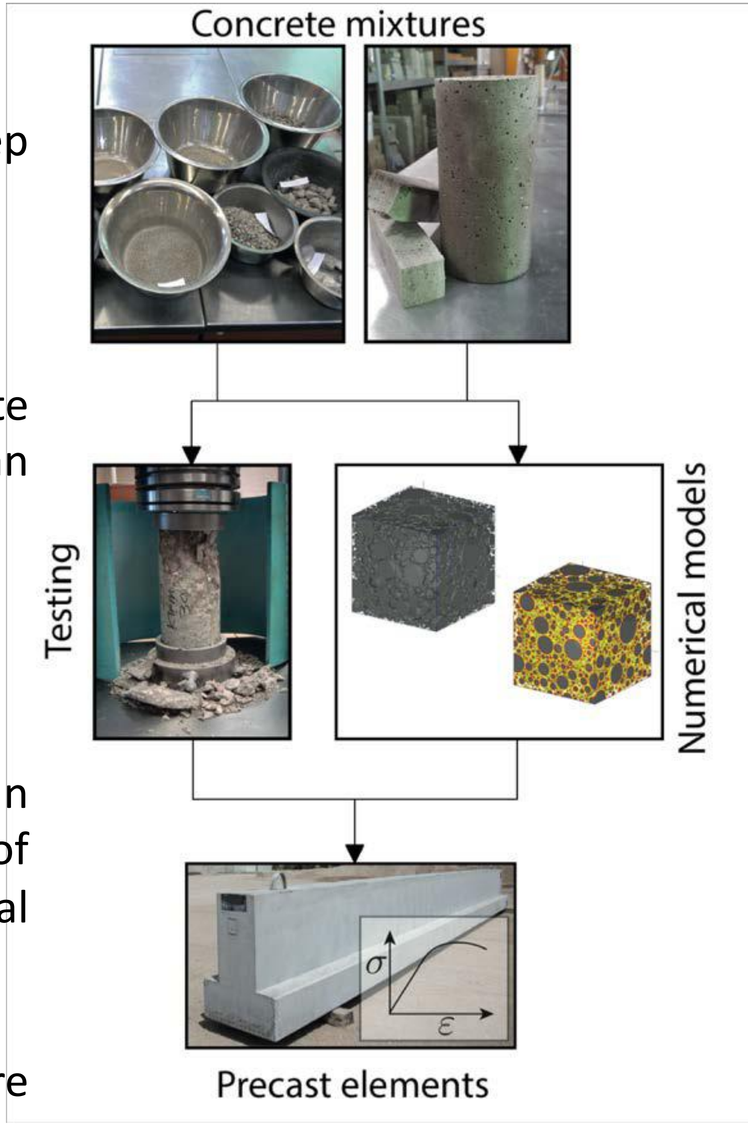
Use recycled aggregates: an important step towards a sustainable development

How to formulate and optimize a concrete made of recycled aggregates at an acceptable price and quality

Develop a new mix design method using an approach based on the combination of experimental techniques and numerical simulation.

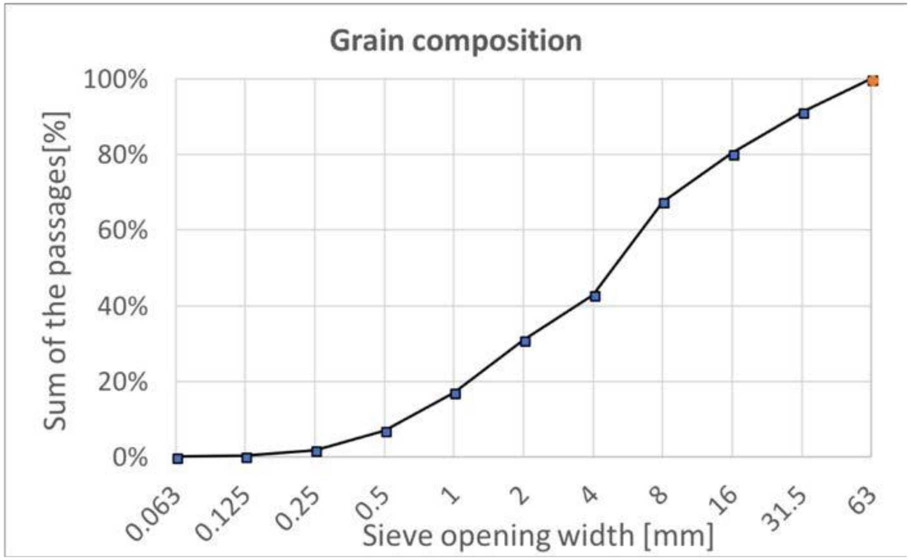
Optimize: Elastic properties, fracture resistance, durability characteristics.



II. Experimental methodologies

Recycled aggregates

- Using recycled aggregates of known origins
- Crushed aggregates provided by Contern S.A: Crushing of the drainage pipes



Granulometry analysis of recycled aggregates

This study

Grade 1: Aggregates with the maximum size of 8 mm

Grade 2: Aggregates with the sieve size from 4 to 8 mm

Evaluation of physical and mechanical properties of recycled aggregates

Bulk density test

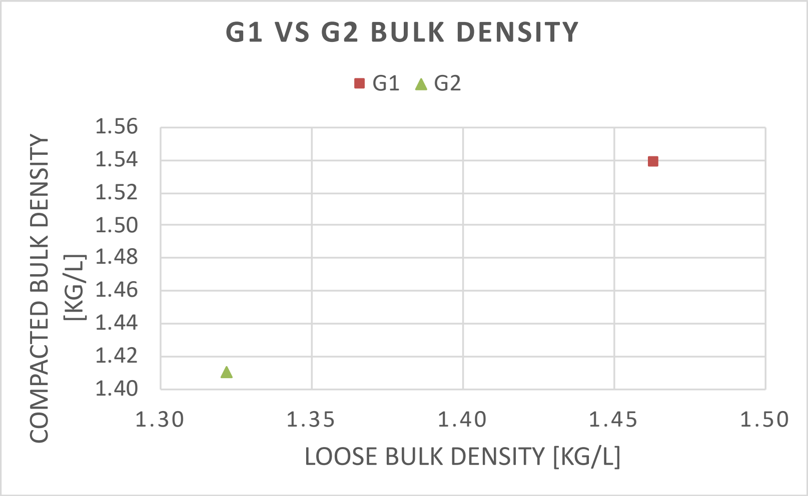
Aggregate Crushing Value Test

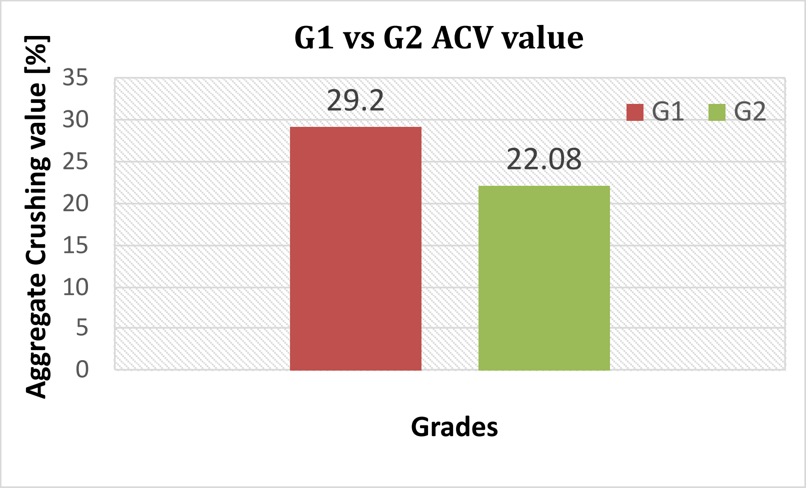
Los Angeles Abrasion Test

Evaluation of physical and mechanical properties of recycled aggregates

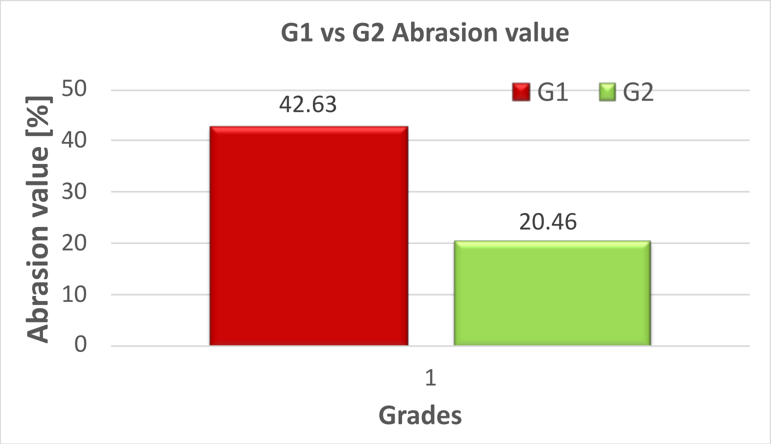
	Loose Bulk Density [Kg/L]	Compacted Bulk Density [Kg/L]
G1 (<8mm)	1.46	1.54
G2 (4mm<=R<=8mm)	1.32	1.41

Aggregate Crushing Value		
ID	Grade	ACV %
G1	<8mm EU sieve	59.20
G2	4mm<=R<=8mm EU sieve	22.08





Los Angeles Abrasion aggregate Test		
ID	Grade	ACV %
G1	<8mm EU sieve	42.63
G2	4mm<=R<=8mm EU sieve	20.46



Evaluation of concrete properties prepared with different grade combinations

Two concrete mixes are developed

- Aggregates (G1 and G2)
- Cement (Filler 3 and P55)
- Admixture (ACE 456 and Micro 104)
- Water

Mix 1-G1: using the aggregates with the maximum size of 8 mm
Mix 2-G2: using the aggregates with the sieve size from 4 to 8 mm

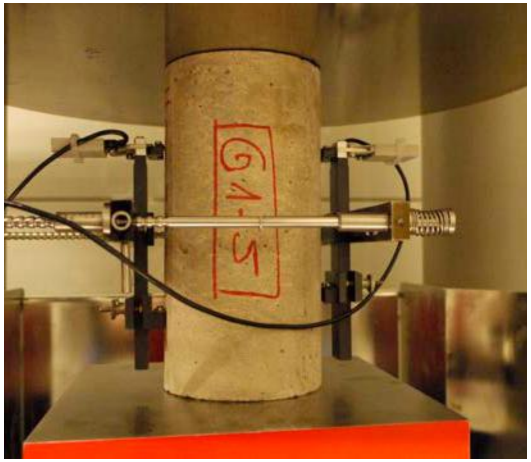
Optimizing the concrete mixes

Water + Admixture

Aggregates (G1)

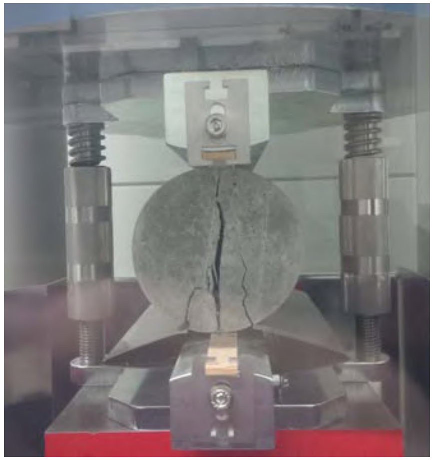
Cement (Filler 3 and P55)

Evaluation of concrete properties prepared with different grade combinations

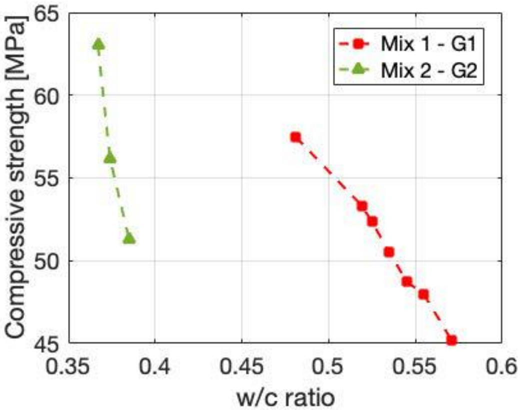


Compression test

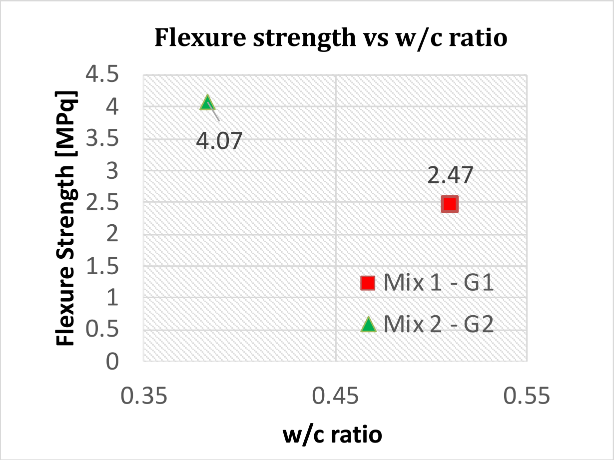
Three point flexural test



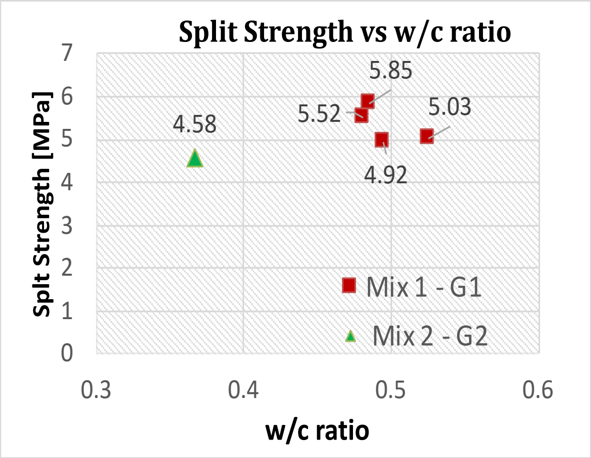
Tensile splitting test



Compressive strength



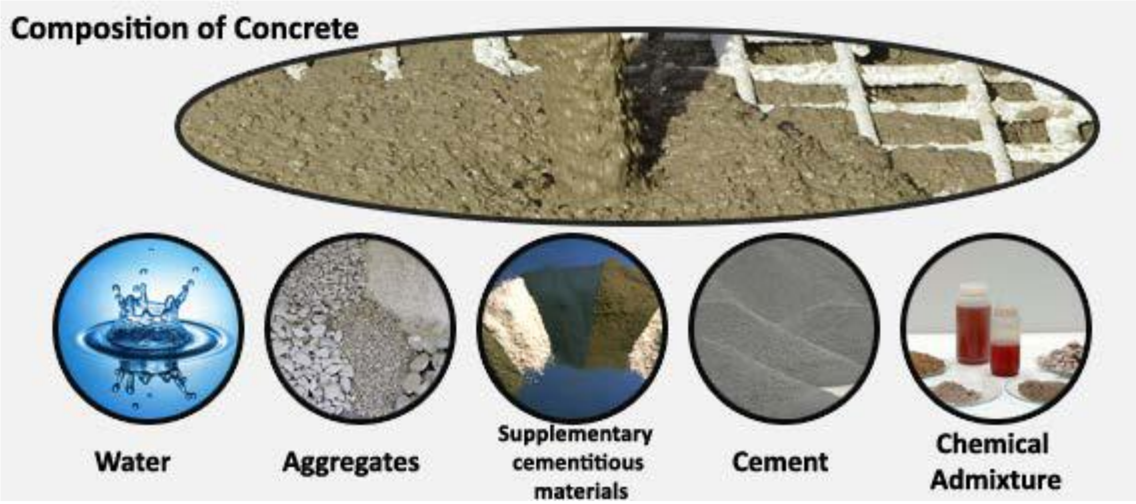
Flexural strength



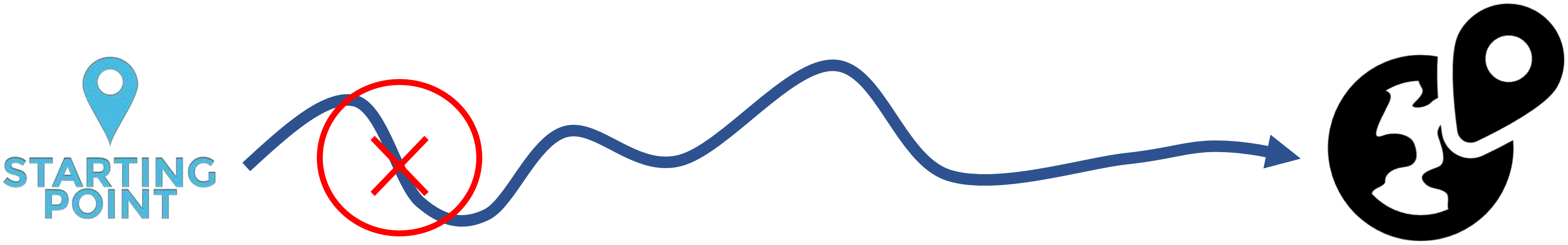
Tensile splitting strength

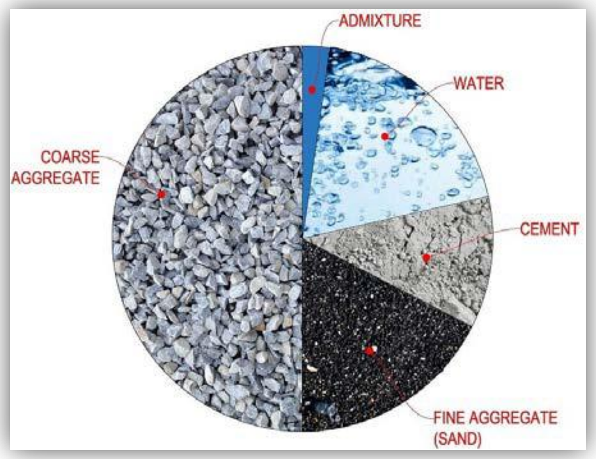
Several preliminary results

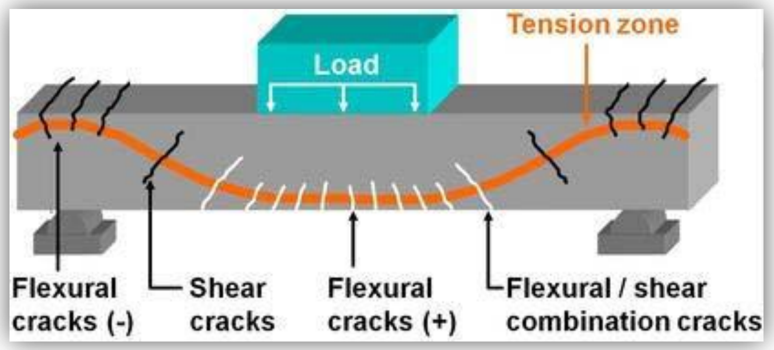
Several results

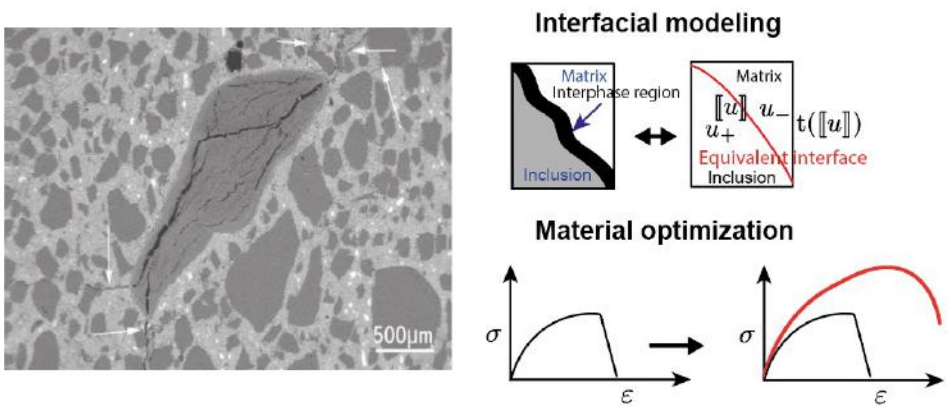


	E [GPa]	Compressive St [MPa]	Flexural St [MPa]	Splitting St [MPa]
Mix I	30.18	57.48	2.47	5.85
Mix II	34.85	63.01	4.07	4.58

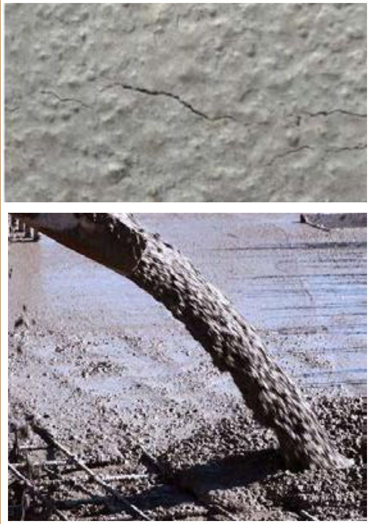






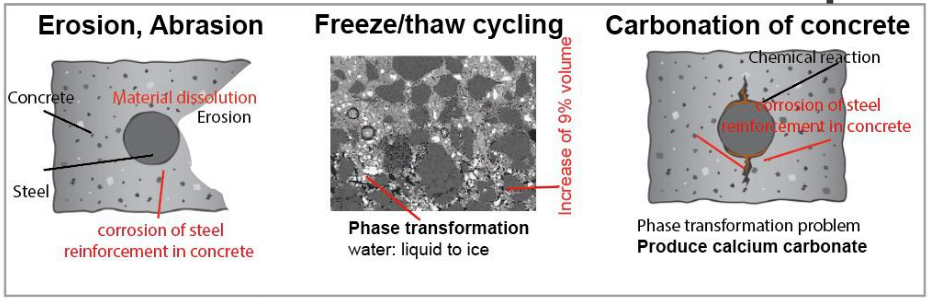


Fracture resistance

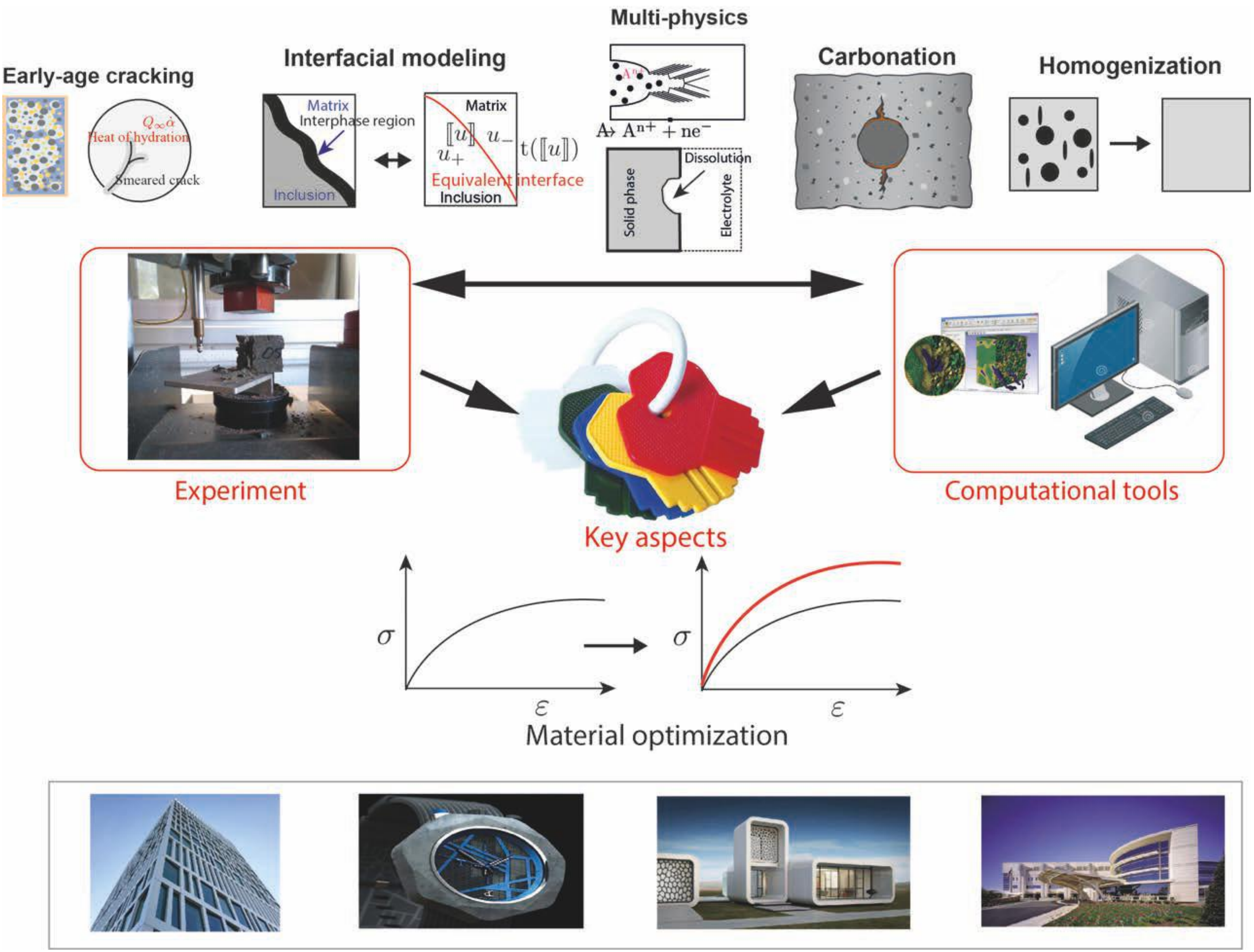


Early-age behaviors

Durability Performance



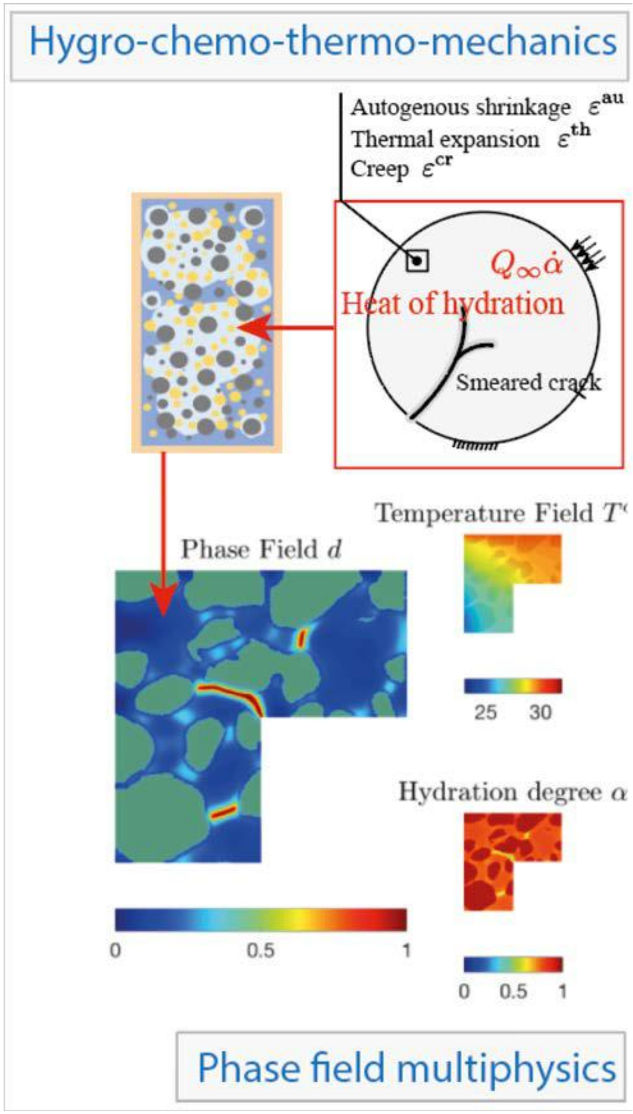
III. Proposed approach



Role of early-age behavior in the concrete durability


Microcracking


Macrocracking



Recycled concretes:

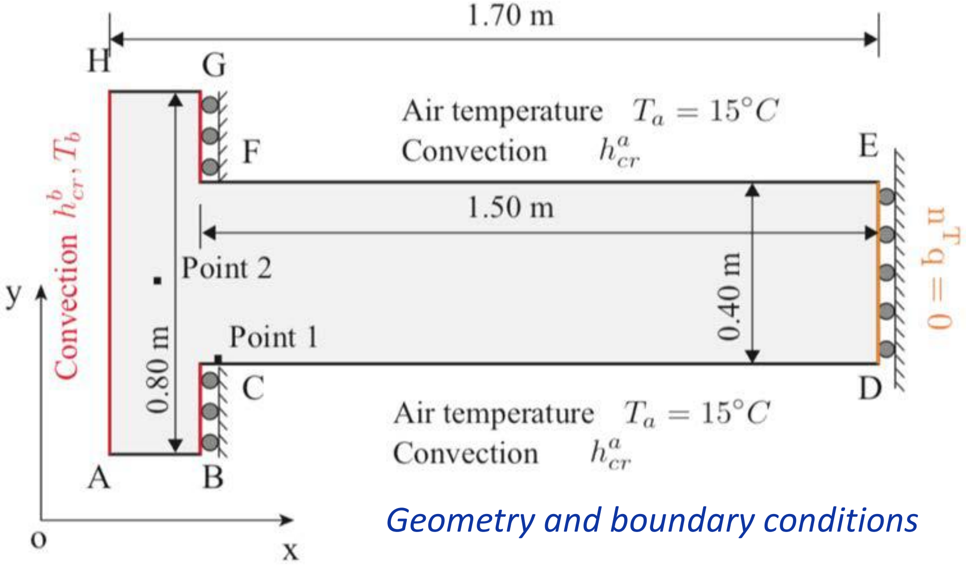
- Increase of the shrinkage
- Sensibility with the early-age cracking
- **Strongly alter the durability performance**

Contributions

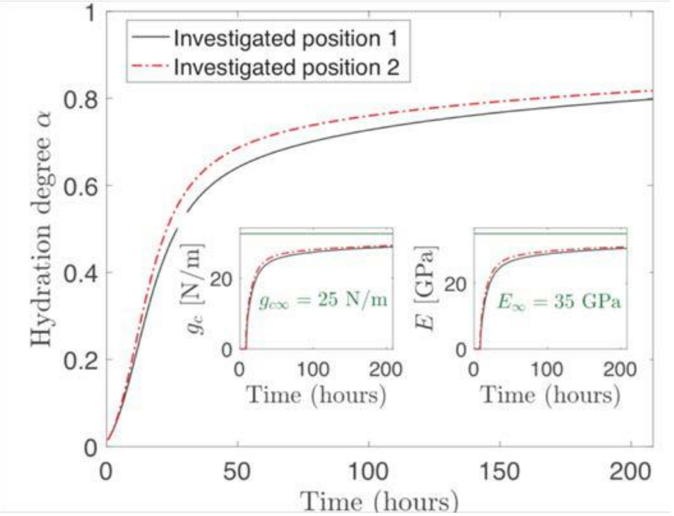
Phase field model with coupled multi-physics process

- Coupling chemo-thermo-mechanical problems
- Heat of hydration, thermal expansion
- Material strength development
- Autogenous shrinkage
- Basic creep, thermal transient creep

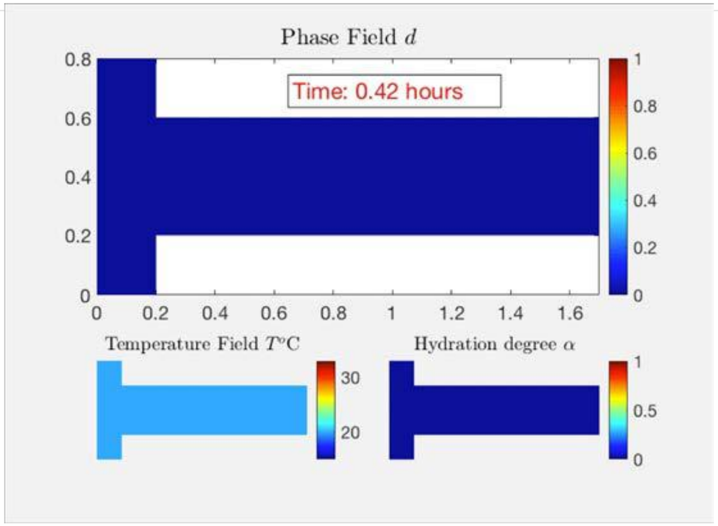
Numerical prediction of the early-age behaviors



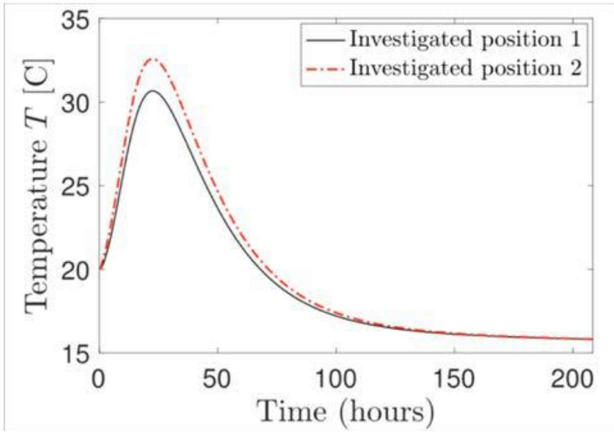
Geometry and boundary conditions



Hydration evolution during hardening process

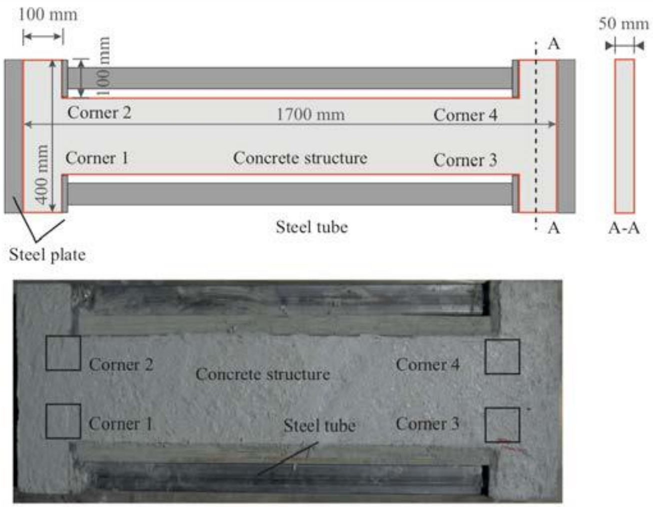


Animation of crack, temperature, hydration evolution during hardening process



Temperature evolution during hardening process

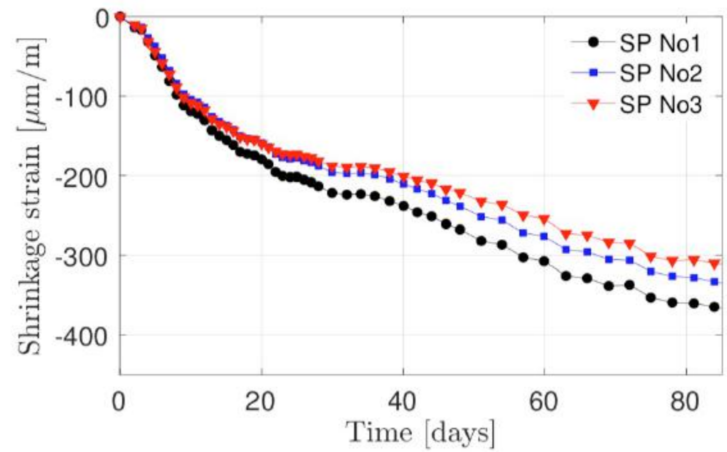
Confronting Model/Experiment: unreinforced concrete



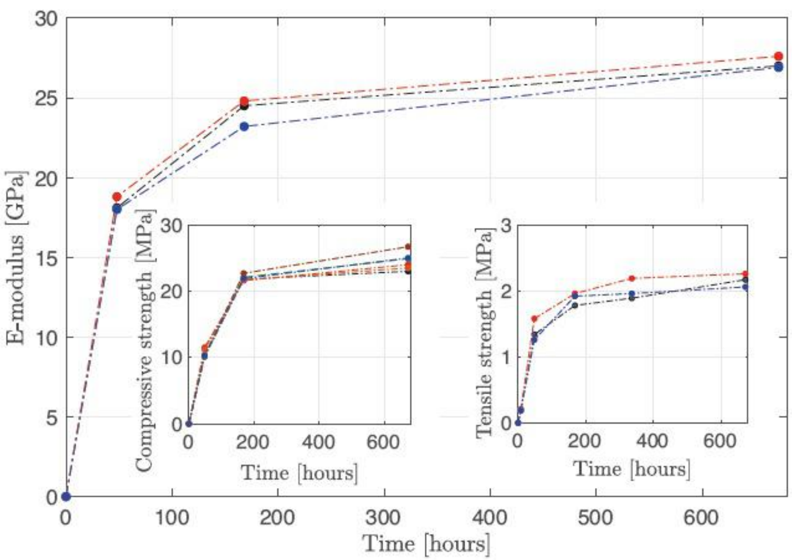
Description of the investigated system

Description of the present concrete mix

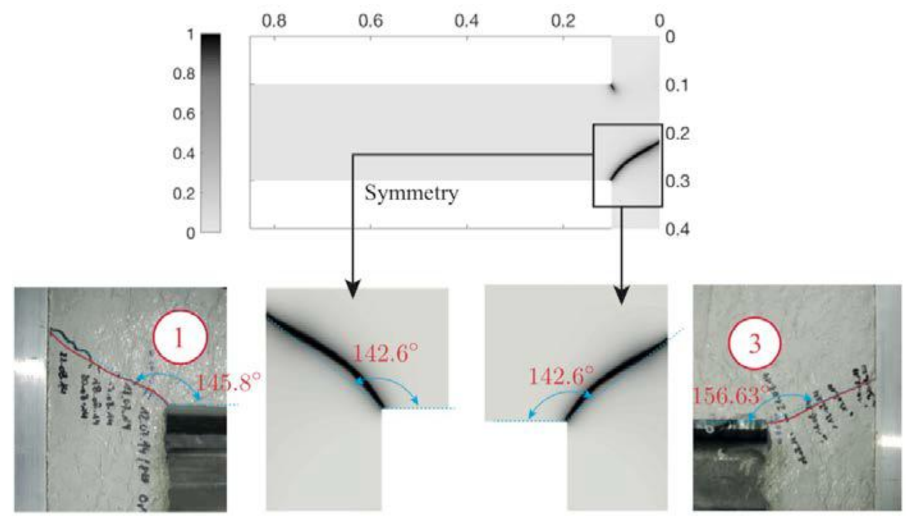
Aggregates	CEM II/A 42.5 N	Water	Unit
1814.2	300	196	[kg/m³]



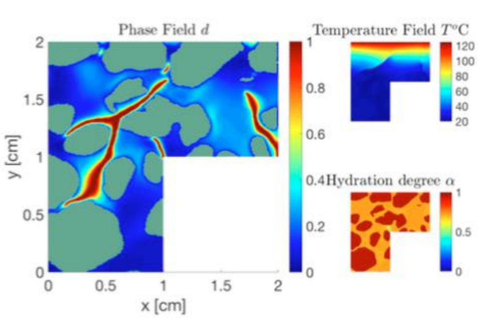
High shrinkage strain: up to 400 $\mu m/m$

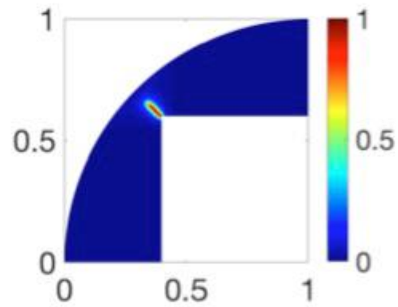


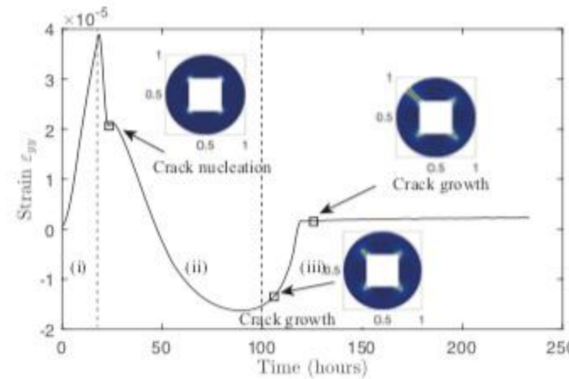
Evolution of material strength



IV. Early-age behavior of recycled aggregate concrete







Several conclusions

- Critical shrinkage properties
- A high risk of cracking
- Major damage cause: thermal expansion and autogenous shrinkage
- Important effects of creeps at the early-age

Solutions should be adapted

- Using admixture: Shrinkage-reducing agent, Super-adsorbent polymer particles
- Changing cement: Portland cement containing higher C2S content
- Internal water curing of concrete
- Replacing normal weight aggregate with pre-saturated lightweight aggregate

Durability of concrete made of recycled aggregates

Purpose

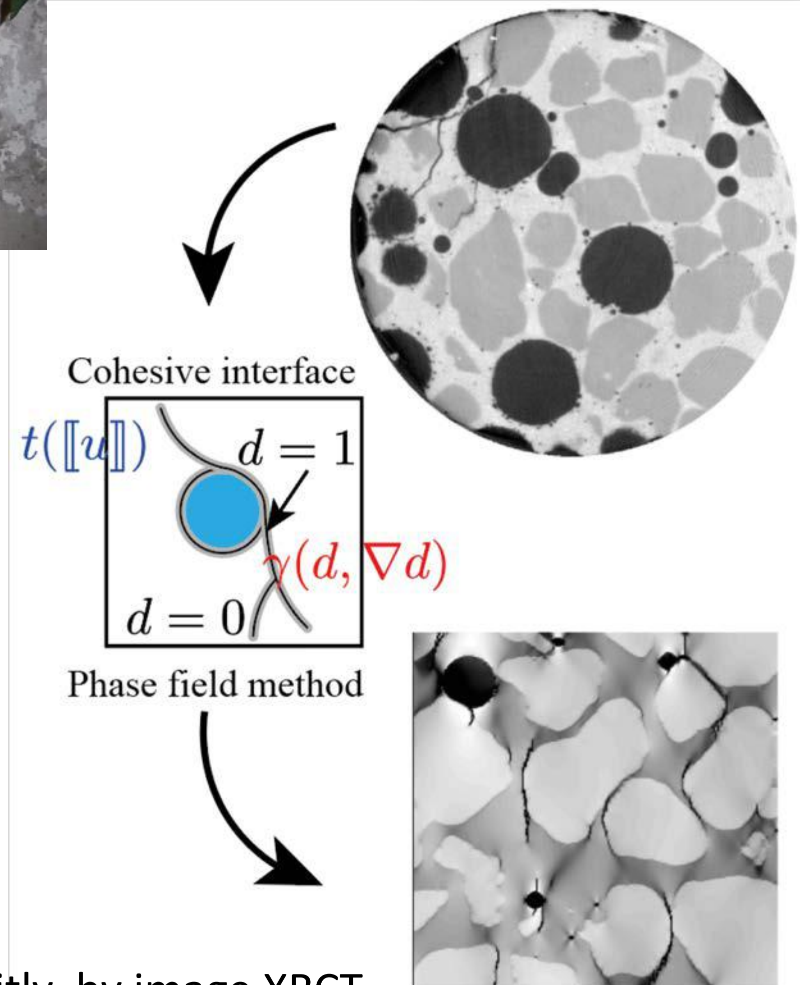
- Developing numerical tool to accurately predict mechanical performance and durability: crack initiation/propagation, fracture resistance.
- Evaluating the effects: aggregates, cements, etc

→ **Key aspects controlling mechanical properties**

Contributions

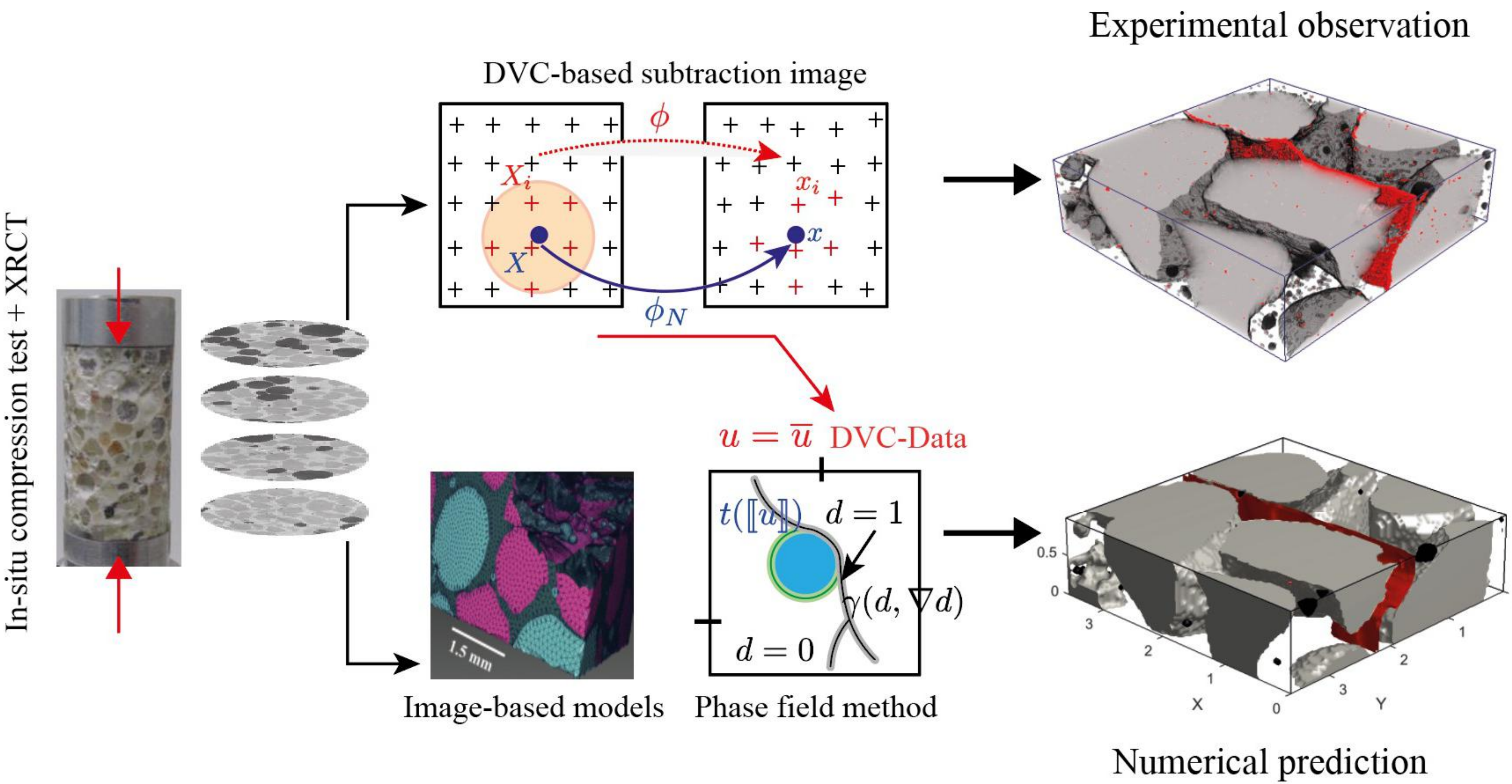
- Numerical framework- Phase field method
- Microcracking - Complex microstructure - explicitly by image XRCT
- Confronting model/experiment

Experiment



Simulation

Confronting between experiment/model



IV. Evaluation of fracture resistance

Analysis of the effects of aggregates and cement

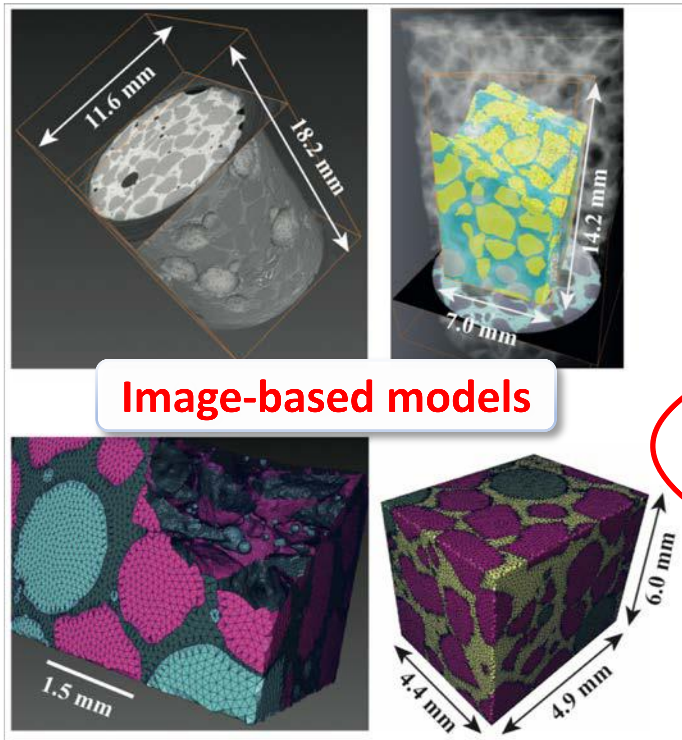
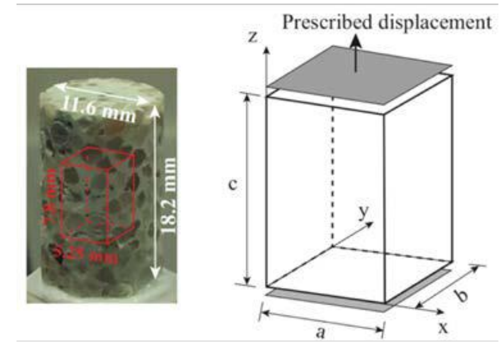
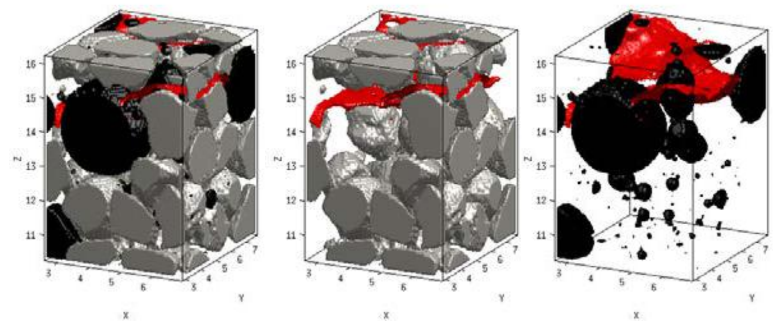


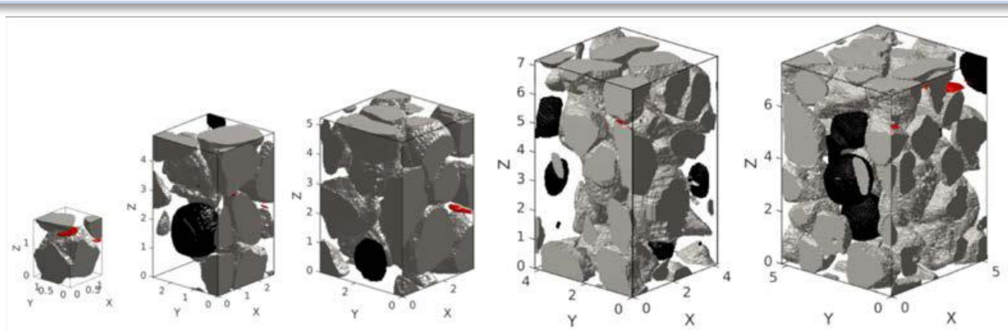
Image-based models



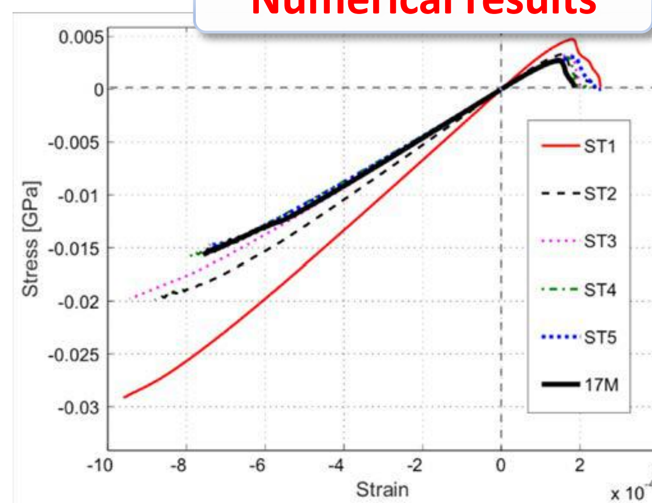
Geometry and boundary conditions

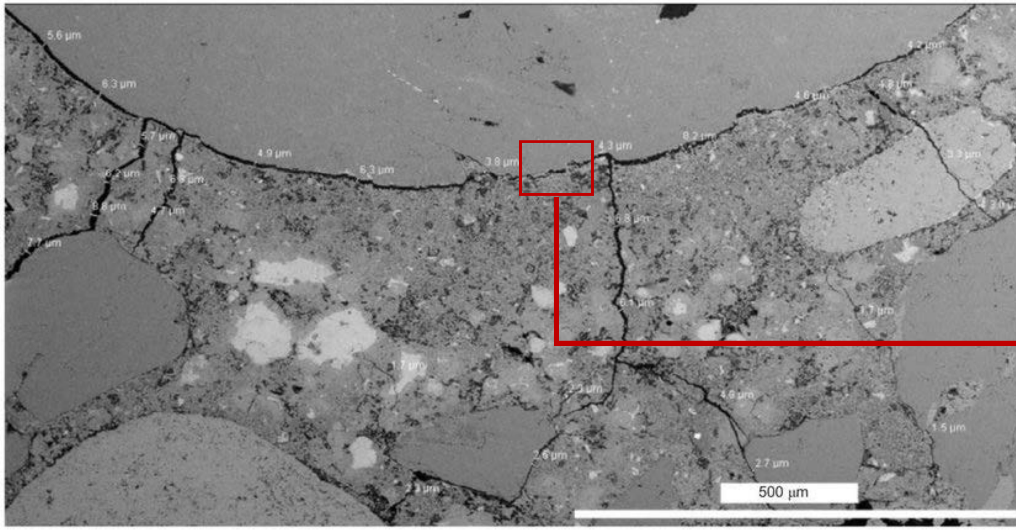


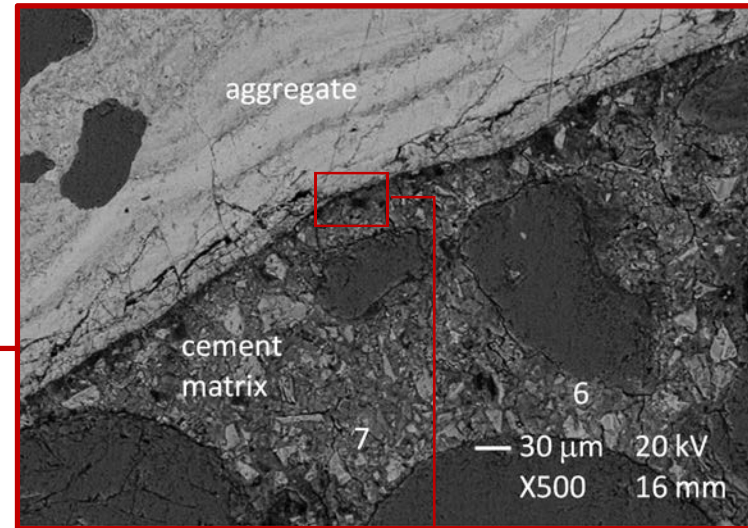
Large-scale simulations of quasi-brittle microcracking in realistic highly heterogeneous microstructures

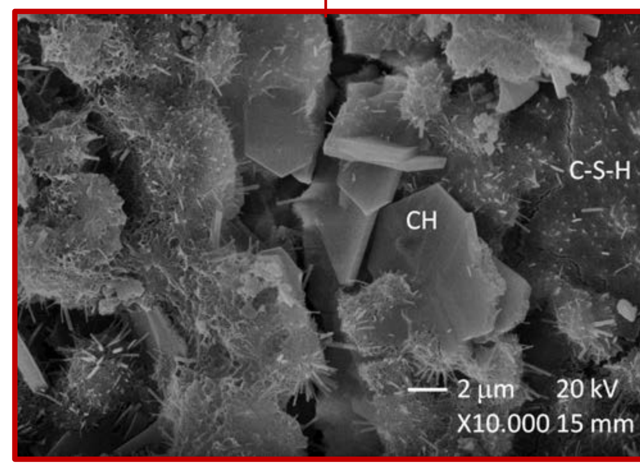


Numerical results









Role of interfacial transition zone

- Weak region
- Preferential zone of cracking
- Strongly affect the strength of concrete materials

What? Why? And How?

How to control the interfacial effects?

Capture interface/interphase effects, is an extremely difficult task.

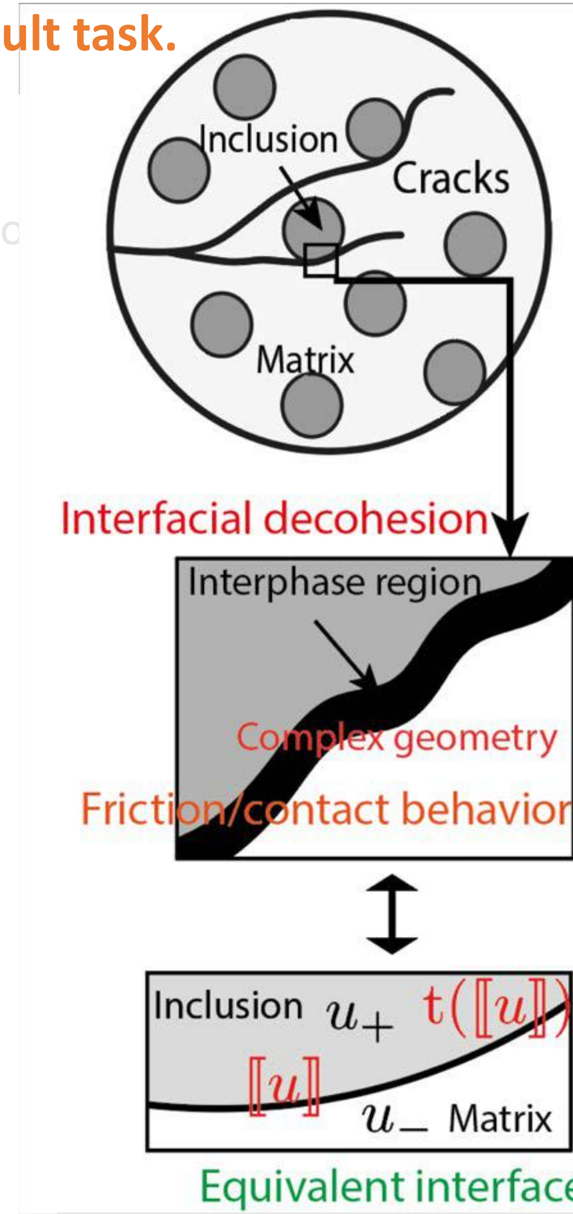
- Complex geometry
- Complex chemical compositio
- Heterogenous in nature
- Size scale

How to de

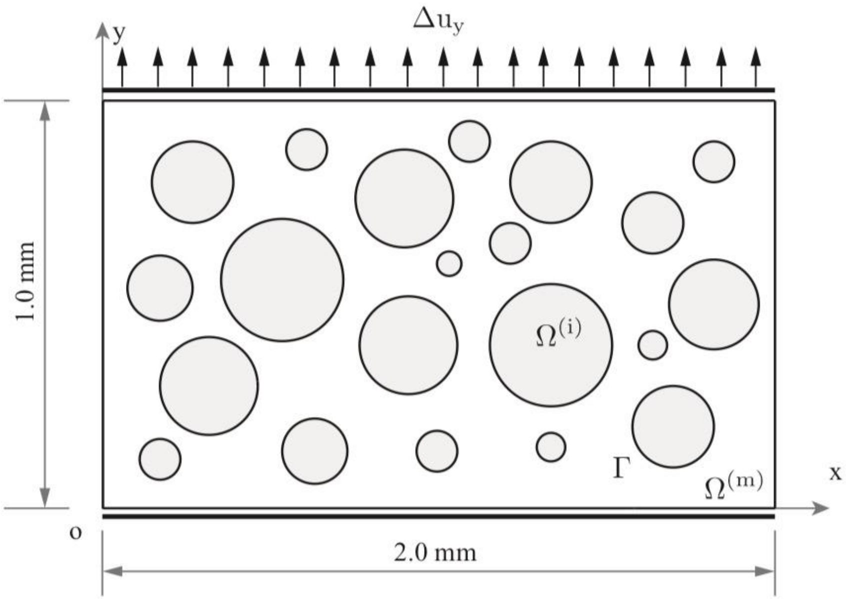
Robust computational model (interface effects)

- Using equivalent interface
- Possibly handle complex geometry/properties of interface
- Accurately predict the mechanical behavior

→ Control the influences of interface
→ Provide the key aspects for material design.



Analysis of interface effects on the global behavior of material



Study cases

- Soft interface (SI1): g_c = 4×10^{-5} [kN/mm]
- Soft interface (SI2): g_c = 2.5×10^{-4} [kN/mm]
- Stiff interface (CI): g_c = 5×10^{-3} [kN/mm]

Material properties

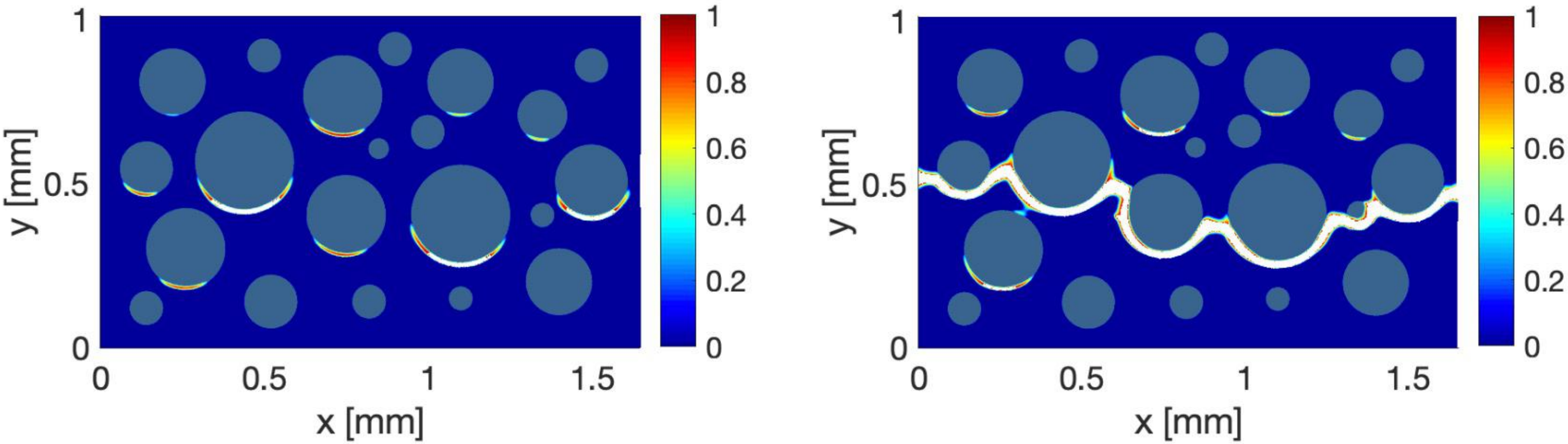
Parameter	Matrix	Inclusion	Soft interface	Stiff interface	Unit
λ	18	60	4.5×10^{-2}	6×10^3	GPa
μ	12	32	3×10^{-2}	4×10^3	GPa

Phases	Fracture resistance [kN/mm]
Matrix	5×10^{-4}
Inclusion	3×10^{-3}

Expectation

- Effects of interface properties
- How it changes mechanical behavior
- Which one is the best solution?

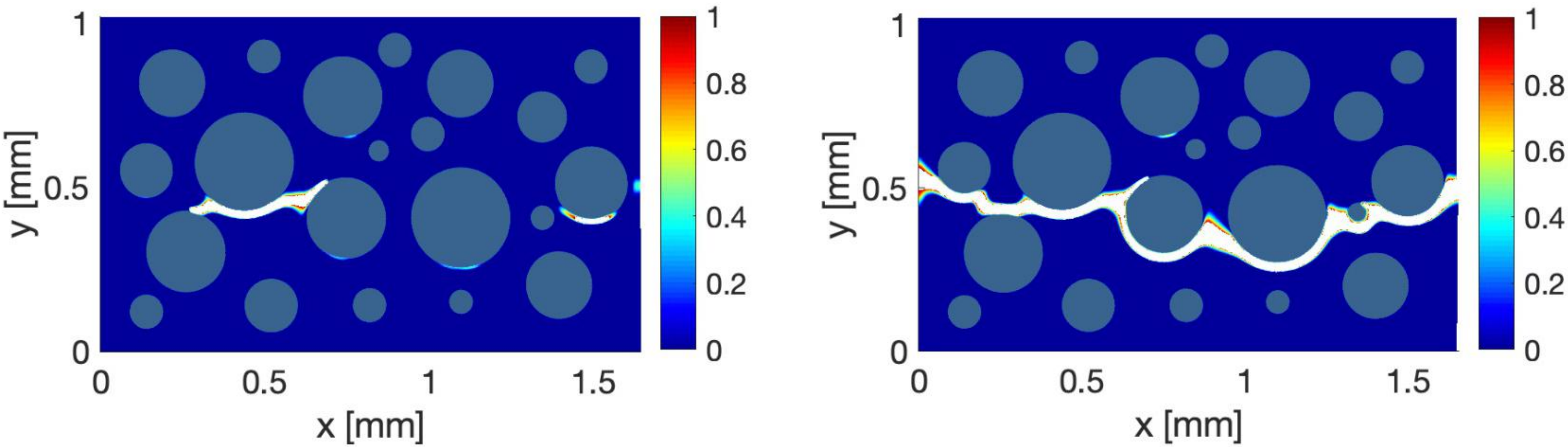
Soft interface (SI1): lowest interfacial fracture resistance



(a) $\overline{\mathrm{U}}_{\mathrm{y}} = 0.0185$ mm (b) $\overline{\mathrm{U}}_{\mathrm{y}} = 0.02236$

Damage/Fracture: mostly in the interfacial regions

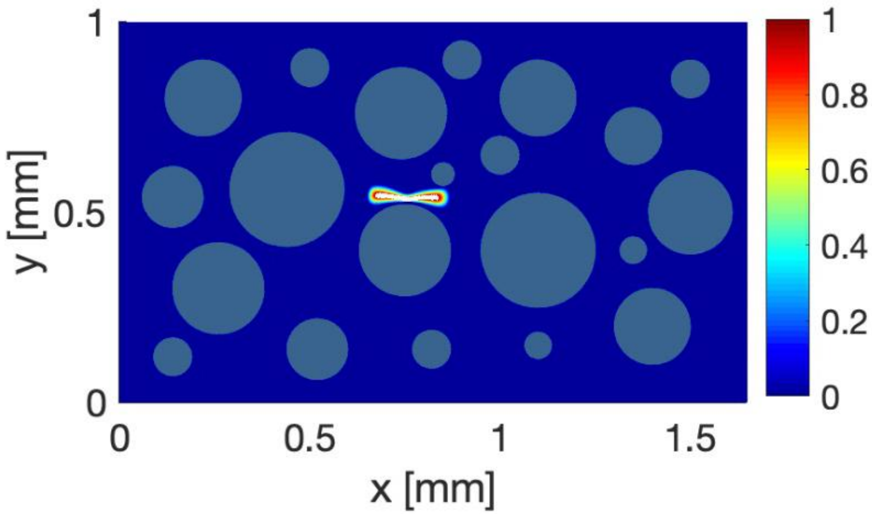
Soft interface (SI2): normal interfacial fracture resistance



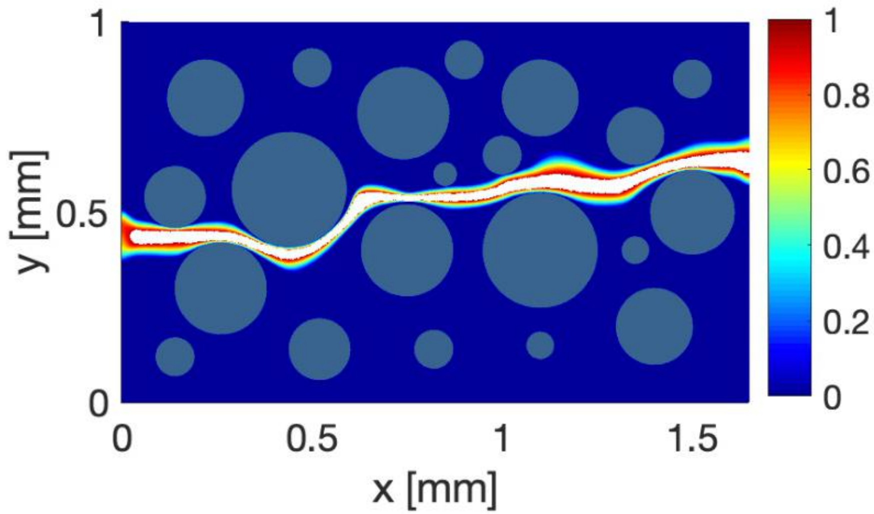
(a) $\overline{\mathrm{U}}_{\mathrm{y}} = 0.0248$ mm (b) $\overline{\mathrm{U}}_{\mathrm{y}} = 0.0260$

Damage/Fracture: in both the interfacial regions and bulk phases

Stiff interface (CI): highest interfacial fracture resistance

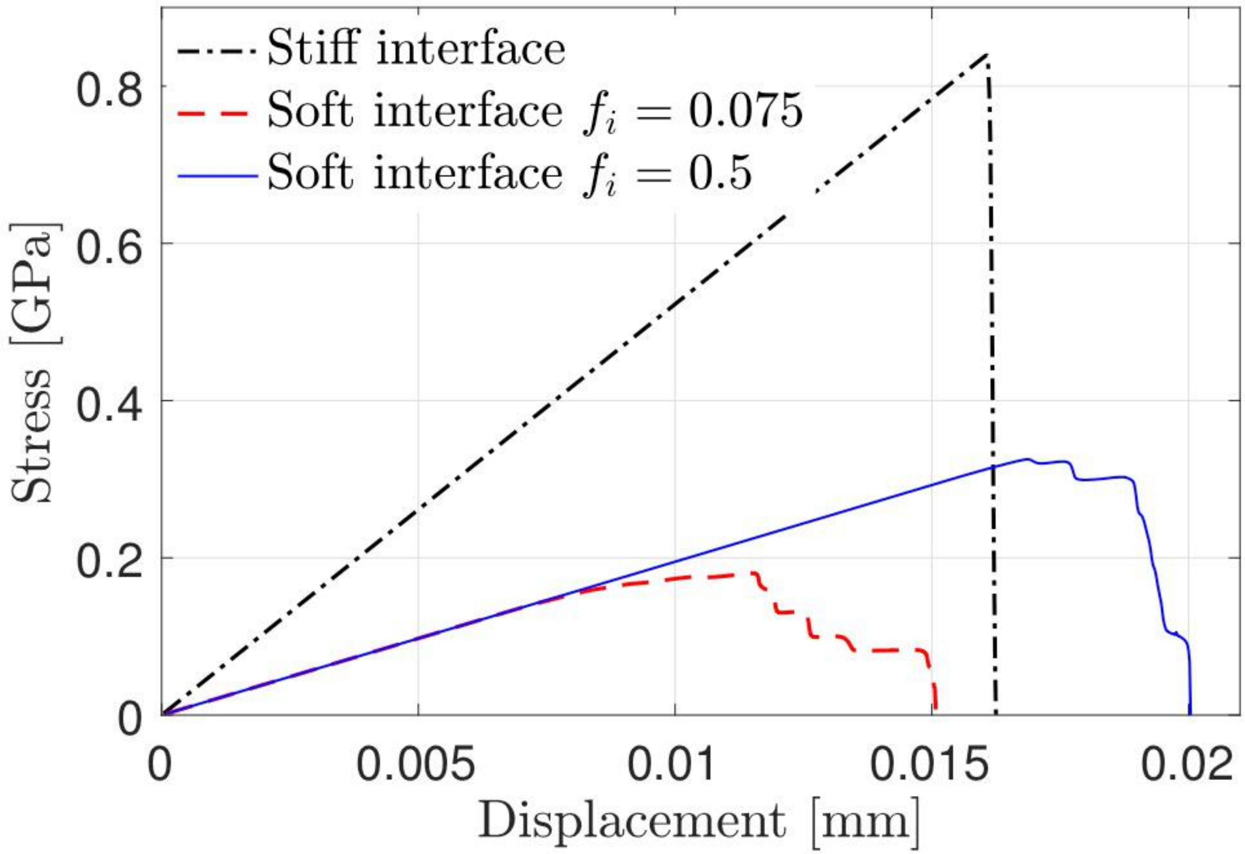


(a) $\overline{\mathrm{U}}_{\mathrm{y}} = 0.01645$ mm



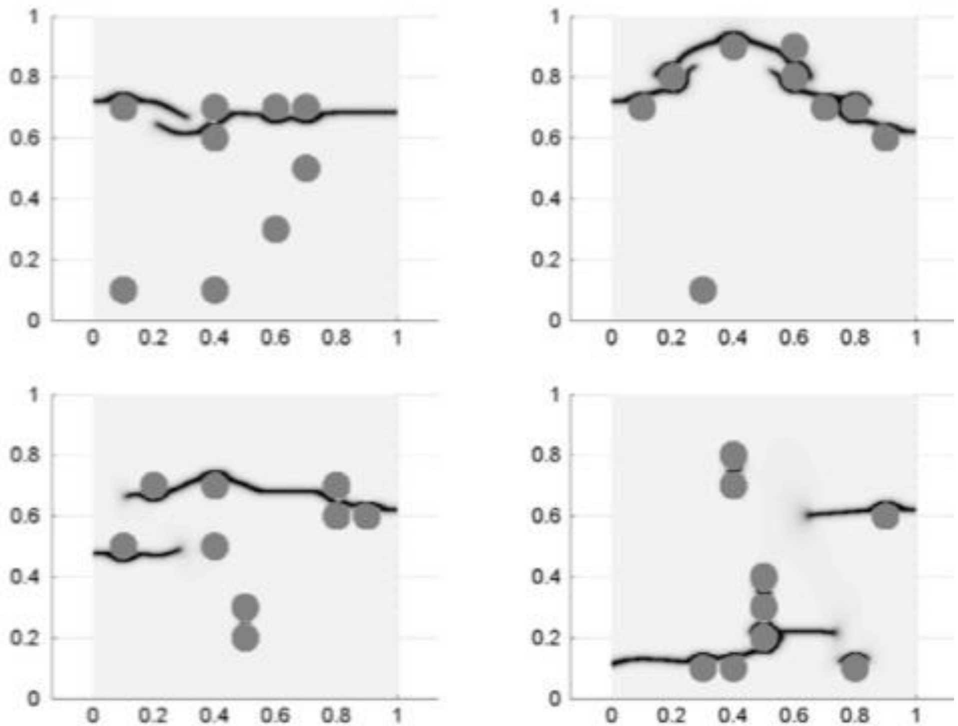
(b) $\overline{\mathrm{U}}_{\mathrm{y}} = 0.01658$

Damage/Fracture: mostly in the bulk phases

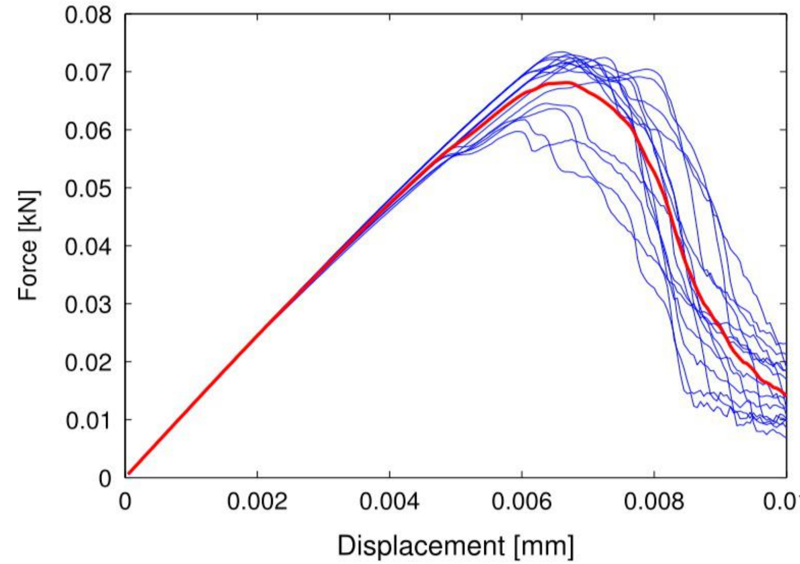


- Soft interface + high interfacial fracture strength: good for **post-cracking behavior**
- Stiff interface + high interfacial fracture strength: increase the **stiffness**

Optimizing morphologies, distributions of heterogeneities



Stochastic simulation



Predicted mechanical performance for different configuration

Conclusion

The effects of constitute behavior, phase morphology, phase distribution, phase size scale, and interphase bonding on fracture toughness. In particular, a combination of fine microstructure size scale, smooth aggregate morphology, appropriately balanced interphase bonding strength and compliance can enhance the fracture toughness.

Several conclusions

- Low fracture resistance
- High risk of damage/cracking
- Strong impacts of interfacial behaviors

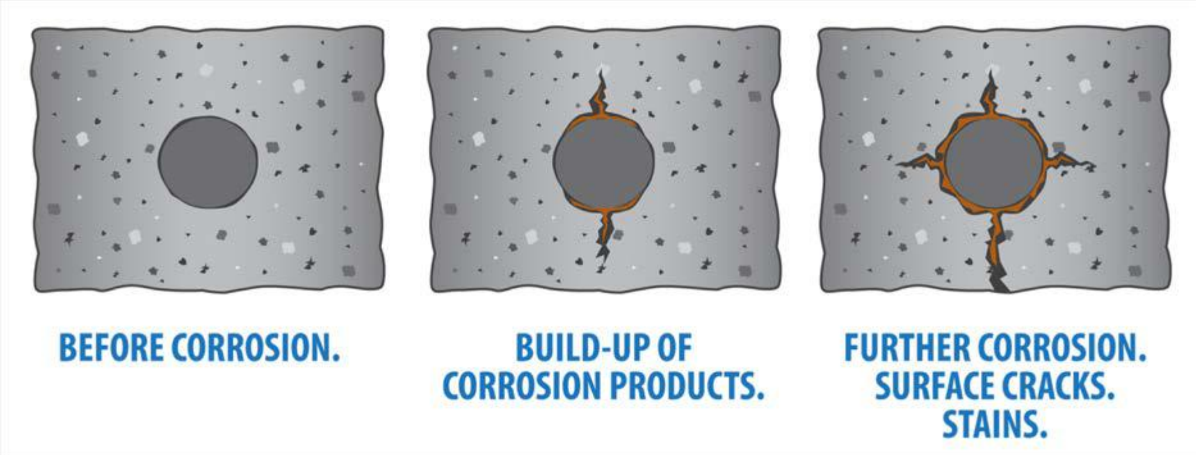
Beside the ratio Cement – Water – Aggregates and admixtures

- Optimize the morphologies of the aggregates
- Improve the bonding cement/aggregate
- Enhance the distribution of heterogeneities (aggregates)

Need to be investigated more

- Different interface types in recycled concretes
- Inelastic behavior due to complex interfaces
- Damping performance

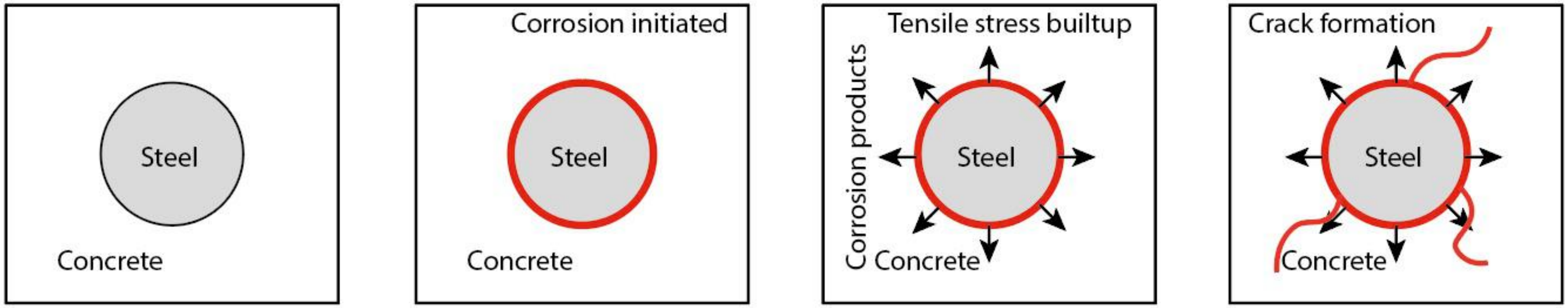
Reinforcement corrosion in concrete structures



- Carbonation, chloride,…
- Cement composition
- **Impurities in aggregates**
- Admixtures
- w/c ratio
- Cement content

Corrosion products take up more volume than the original steel consumed, a pressure is build up in the interface between reinforcement and concrete. The increase in pressure eventually leads to cracking of the concrete cover

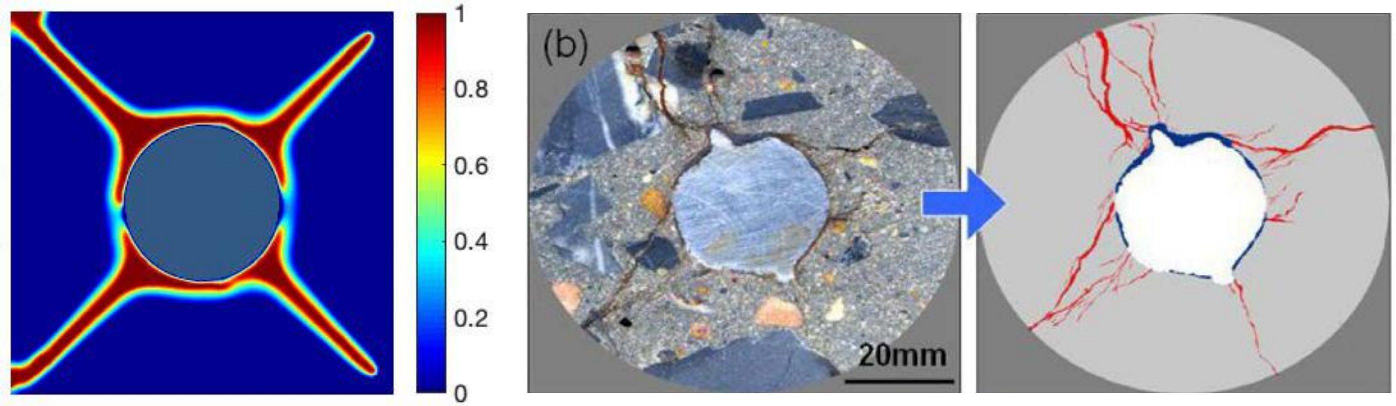
Numerical modeling of cracking of concrete due to corrosion



Phase transformation model +Interfacial decohesion

Phase field model

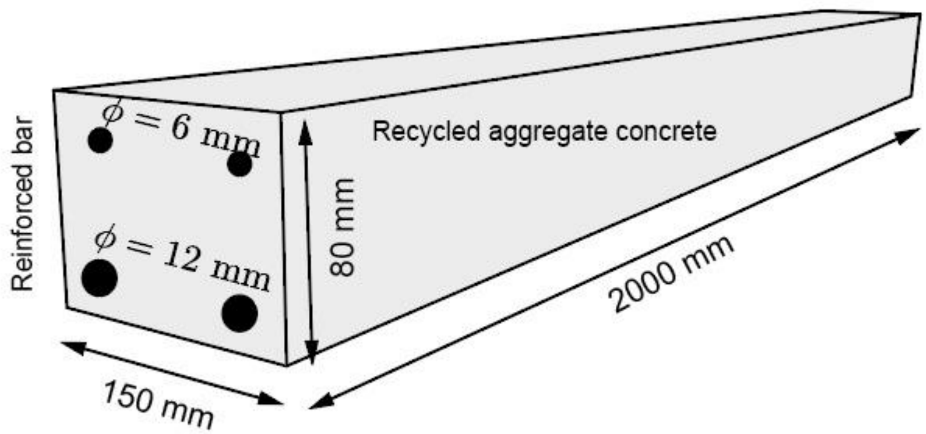
Numerical modeling of cracking of concrete due to corrosion



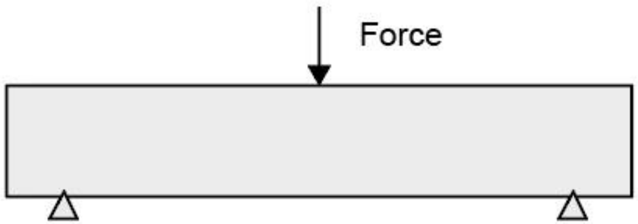
Recycled Concrete is cracked at the strain expansion (of steel): 0.3 %

There are several factors related to the recycled concrete quality, which could lead to corrosion problem, such as w/c ratio, cement content, impurities in the concrete ingredients, presence of surface cracks, etc.

Behavior of recycled aggregate concrete in a real application



Reinforced concrete beam

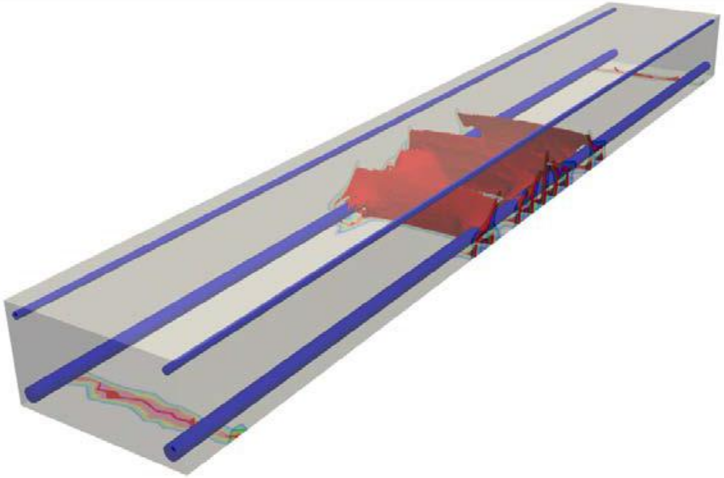


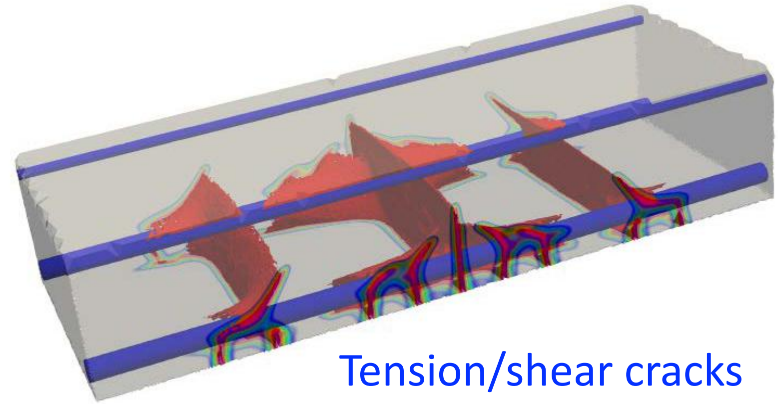
Boundary conditions

Material properties

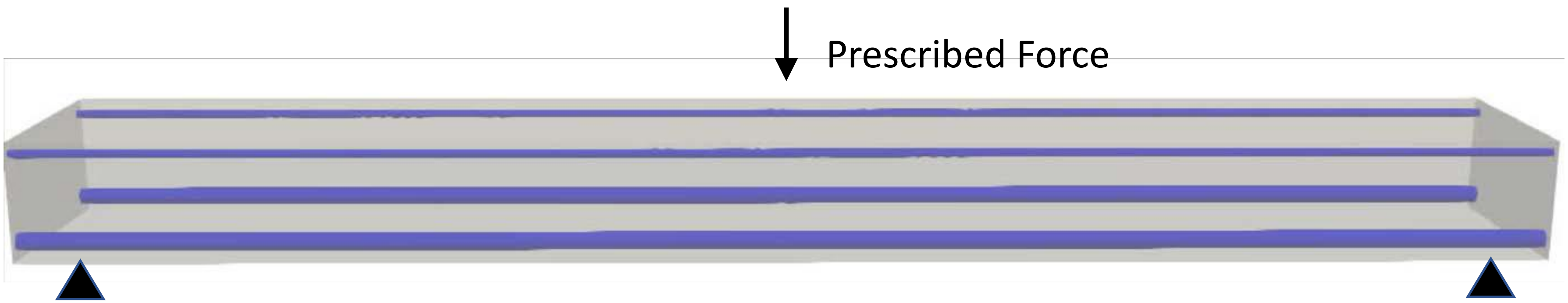
	E [GPa]	Poisson's ration	Fracture energy [N/m]	Tensile strength [MPa]
Concrete **(Mix I)**	30.18	0.22	124	5.4
Steel bar	250	0.3	9310	463

Behavior of recycled aggregate concrete in a real application





Observed fracture phenomena



Crack spacing of reinforced concrete

The recycled aggregates concrete gives a comparable resistance

Conclusions

Formulate/optimize new concrete mixtures made of recycled aggregates

- Characterize physical/mechanical properties of aggregates
- Characterize the mechanical performance of recycled aggregates concrete

- Propose new approach combining experiment and model
  - Early-age behavior
  - Fracture resistance
  - Durability performance
  - Real applications

→ **Define several designed factors**