TU 1404
COST ACTION

www.tu1404.eu

Presentations eBook

2nd WORKSHOP

FOCUS ON MODELLING OF CEMENT-BASED MATERIALS AND STRUCTURES

Vienna, Austria, 19-20 September 2015

European Science Foundation
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cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Editors: Mateusz Wyrzykowski, Farid Benboudjema, Miguel Azenha, Stéphanie Staquet, Dirk Schlicke

Assistance: Core Group of the COST Action TU1404

TU 1404 COST ACTION

COST
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

COST (European Cooperation in Science and Technology) is a pan-European intergovernmental framework. Its mission is to enable break-through scientific and technological developments leading to new concepts and products and thereby contribute to strengthening Europe's research and innovation capacities.

It allows researchers, engineers and scholars to jointly develop their own ideas and take new initiatives across all fields of science and technology, while promoting multi- and interdisciplinary approaches. COST aims at fostering a better integration of less research intensive countries to the knowledge hubs of the European Research Area. The COST Association, an International not-for-profit Association under Belgian Law, integrates all management, governing and administrative functions necessary for the operation of the framework. The COST Association has currently 36 Member Countries. www.cost.eu

Acknowledgement

This eBook is based on work from COST Action TU 1404, supported by COST.

About COST ACTION TU1404

Cement-based materials (CBM) are the foremost construction materials worldwide. Therefore, there are widely accepted standards for their structural applications. However, for service life designs, current approaches largely depend on CBM strength class and restrictions on CBM constituents.

Consequently, the service life behaviour of CBM structures is still analyzed with insufficiently rigorous approaches that are based on outdated scientific knowledge, particularly regarding the cumulative behaviour since early ages. This results in partial client satisfaction at the completion stage, increased maintenance/repair costs from early ages, and reduced service life of structures, with consequential economic/sustainability impacts.

Despite significant research advances that have been achieved in the last decade in testing and simulation of CBM and thereby predicting their service life performance, there have been no generalized European-funded Actions to assure their incorporation in standards available to designers/contractors.

The main purpose of COST TU1404 Action is to bring together relevant stakeholders (experimental and numerical researchers, standardization offices, manufacturers, designers, contractors, owners and authorities) in order to accelerate knowledge transfer in the form of new guidelines/recommendations, introduce new products and technologies to the market, and promote international and inter-speciality exchange of new information, creating avenues for new developments.

About the 2nd Workshop of COST ACTION TU1404

The 2nd workshop had several objectives related to Work Group 2 (Modelling of Cement-based Materials and Structures) of the Action:

- to promote scientific discussion on the modelling activities, models development, etc. between the members of the Action as well as with the invited external participants;
- to integrate the modelling community within the Action;
- to discuss further developments leading to recommendations/guidelines in collaboration with WG3;
- to share ideas and extend the contents of the simple benchmarking campaign;
- to discuss and define a draft of benchmarking activities related to the experimental results of WG1;
- to discuss and define benchmarking activities related to case studies.

In addition to the scientific activities, the 2nd MC meeting of the Action took place during the workshop (20 September 2015).

Place and dates of the workshop:

Vienna University of Technology (TU Wien), Vienna, Austria, 19-20 September 2015.

Number of participants: 77 participants representing 27 countries

Webpage of the workshop: http://www.tu1404.eu/september-2015-vienna

About the 2nd Workshop of COST ACTION TU1404

Photos: Farid Benboudjema, © COST Action TU1404

Contacts

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Stéphanie Staquet sstaquet@ulb.ac.be

PRESENTATIONS

List of presentations (1)

List of presentations (2)

List of presentations (3)

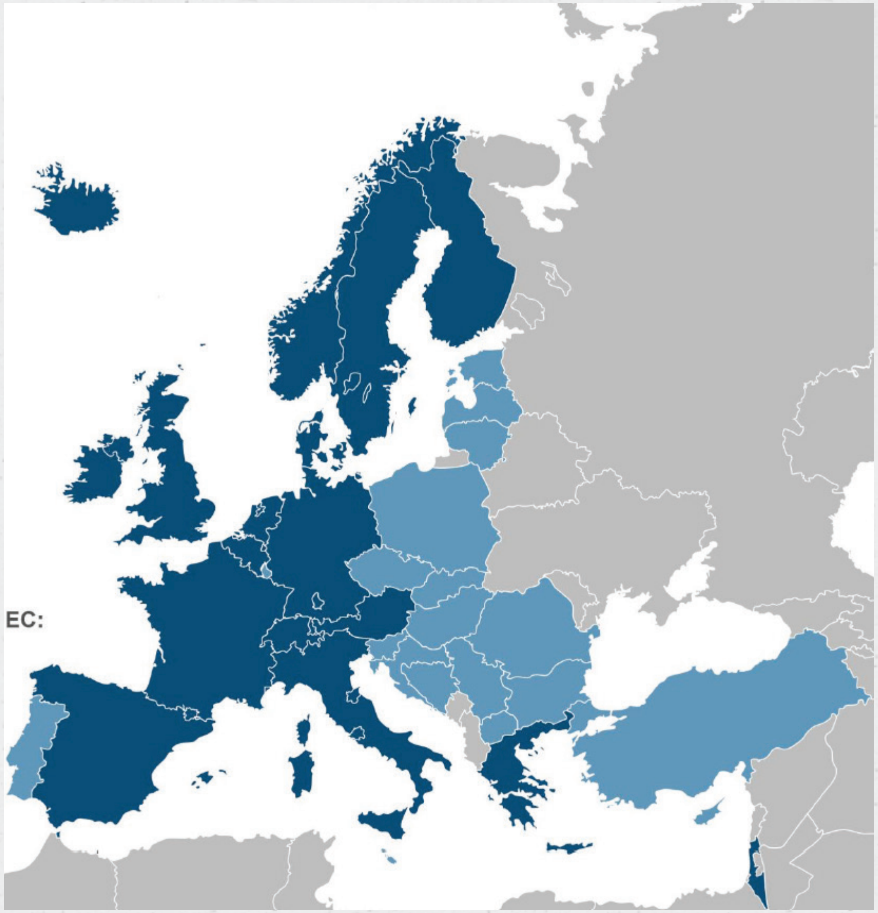
Opening Session

2nd COST TU1404 Meeting – Vienna, September 19-20, 2015

Members of COST TU1404

- 29 COST Countries
- 1 NNC – Ukraine (Algeria also coming in)
- 1 IPC – Australia (Japan also coming in)

- 226 individual members
- 42% are Early Stage Researchers
- Gender balance: 75% Male; 25% Female



What a year! :)

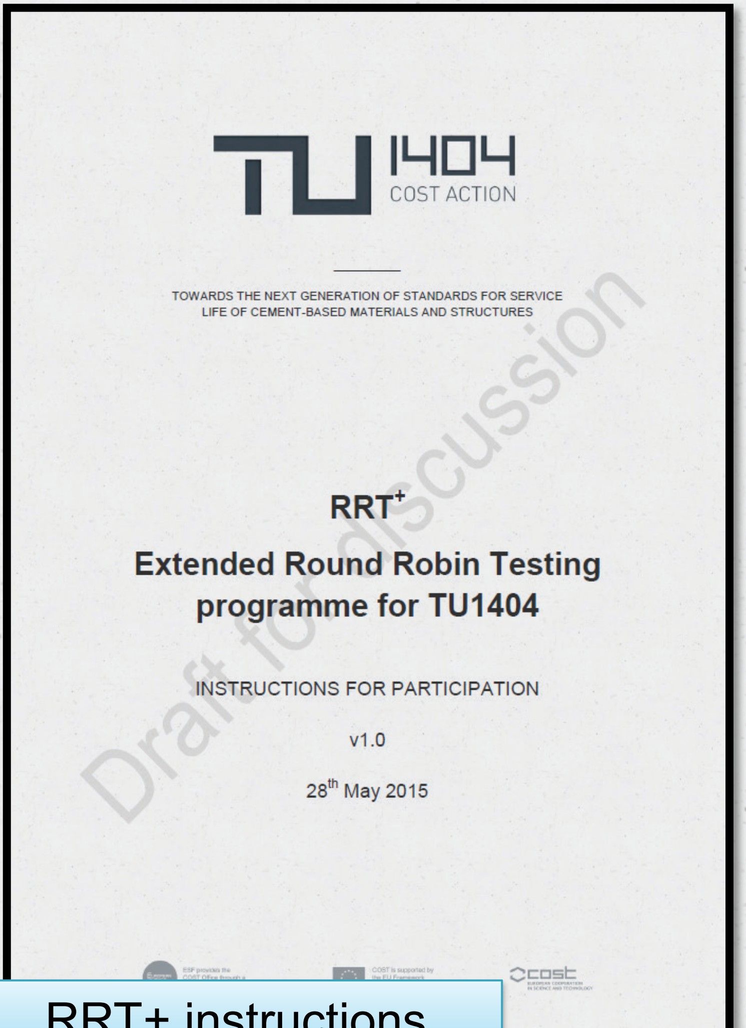
- Ljubljana, Slovenia, April 2015

57 participants

- Vienna, Austria, September 2015

78 participants

What a year! :)



TU 1404 COST ACTION

TOWARDS THE NEXT GENERATION OF STANDARDS FOR SERVICE LIFE OF CEMENT-BASED MATERIALS AND STRUCTURES

RRT+

Extended Round Robin Testing programme for TU1404

INSTRUCTIONS FOR PARTICIPATION

v1.0

28th May 2015

RRT+ instructions

eDF

Raw materials supply

BUILDING TRUST Sika

GSM Italcementi Group

Materials on the way!

CEVA

What a year! :)

- Total of 6 STSM's

Portugal
Switzerland

France
Belgium

Belgium
France

Spain
Portugal

UK
Germany

Ukraine
UK

Leaflet of TU1404

Leaflet of TU1404

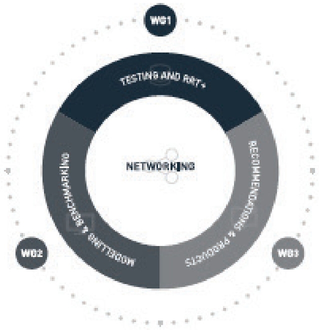
MOTIVATION AND OBJECTIVES

—

Cement-based materials (CBM) are the foremost construction materials worldwide. Therefore, there are widely accepted standards for their structural applications. However, for service life designs, current approaches largely depend on CBM strength class and restrictions on CBM constituents. Consequently, the service life behaviour of CBM structures is still analysed with insufficiently rigorous approaches that are based on outdated scientific knowledge, particularly regarding the cumulative behaviour since early ages.

This results in partial client satisfaction at the completion stage, increased maintenance/repair costs from early ages, and reduced service life of structures, with consequential economic/sustainability impacts. Despite significant research advances that have been achieved in the last decade in testing and simulation of CBM and thereby predicting their service life performance, there have been no generalized European-funded Actions to assure their incorporation in standards available to designers/contractors.

Therefore, the main purpose of this Action is to bring together relevant stakeholders (experimental and numerical researchers, standardization offices, manufacturers, designers, contractors, owners and authorities) in order to accelerate knowledge transfer in the form of new guidelines/recommendations, introduce new products and technologies to the market, and promote international and inter-speciality exchange of new information, creating avenues for new developments.



NETWORKING TOOLS IN THE SCOPE OF COST ACTIONS

—

Short term scientific missions (STSM's), Training schools, Meetings, Workshops, Conferences and Dissemination activities. See more details about these tools in http://www.cost.eu/COST_Actions/networking. To join the action and become eligible to benefit from the networking tools, please check at www.tu1404.eu.

GENERAL LEADERSHIP

—

Chair: Miguel Azenha, University of Minho, Portugal
Vice-Chair: Stéphanie Staquet, ULB Bruxelles, Belgium
General Secretary: Dirk Schlicke, Graz University Of Technology, Austria

WG1
TESTING OF CEMENT-BASED MATERIALS AND RRT+

—

Grega Tritnk, Igmat, Slovenia
Marijana Serdar, University of Zagreb, Croatia
Sreejith Nanukuttan, Queen's University Belfast, United Kingdom

Workgroup 1 deals with experimental testing of properties of cement based materials including eco concrete mixtures. The Extended Round Robin Testing Programme, also called RRT+ involves the sharing of raw materials for concrete, mortar and cement paste. More than 60 tons of cement and aggregates are disseminated among the participants in a common experimental program of unprecedented dimensions in the scope of cement-based materials.

WG2
MODELLING AND BENCHMARKING

—

Mateusz Wyrzykowski, Empa Switzerland and Lodz University of Technology, Poland
Farid Benboudjema, ENS Cachan, France

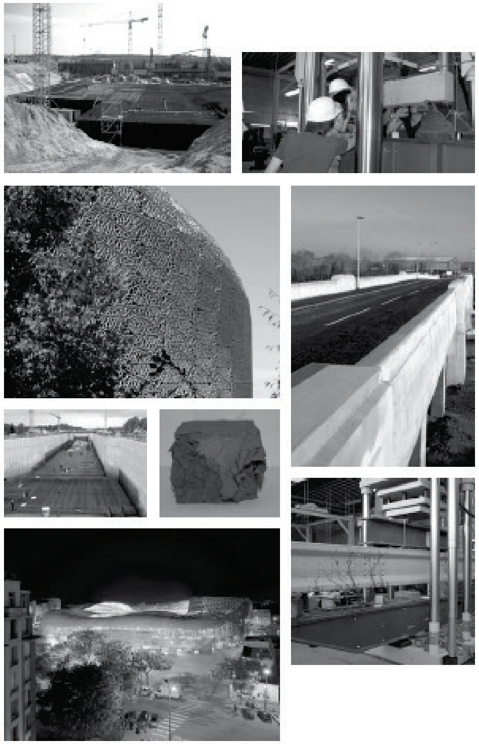
Workgroup 2 deals with modelling of cement based materials and reinforced concrete structures including service life-related aspects. The final objective is to integrate the conclusions to create a set of general instructions to be used in designing software. International benchmarking efforts are being made as to exchange knowledge and inter-comparison of modelling capabilities at different scales (from cement paste to structural level).

WG3
RECOMMENDATIONS AND PRODUCTS

—

François Toutlemonde, Ifsttar, France
Terje Kanstad, NTNU Trondheim, Norway

Proposals for comprehensive and upgraded test standards and development of associated devices constitute a first objective of Workgroup 3. This group will propose a methodology compatible with the Eurocode standard format to address thermo-hydro-mechanical coupled effects in serviceability design. They will focus on identified shortages of present reference documents and on mature developments of tests, products and methods, to contribute to standards and guidelines improvement in the field of service-life design.



Video of TU1404

Watch the video online

Enjoy and profit!

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Multiscale continuum micromechanics: application to cementitious materials

Bernhard Pichler, Christian Hellmich

Vienna University of Technology (TU Wien)
Institute for Mechanics of Materials and Structures

Outline:

- Fundamental aspects
  - Why multiscale modeling?
  - Modeling philosophy in continuum micromechanics

- Application to cementitious materials
  - Elasticity homogenization
  - Strength homogenization
  - Creep homogenization

- Conclusions

- References

Why multiscale analysis?

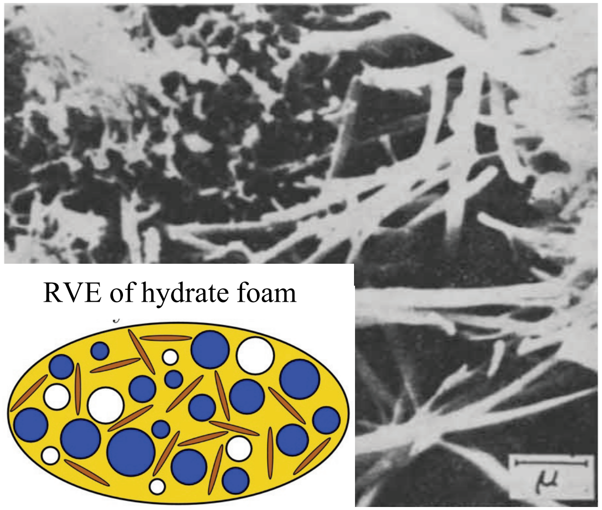
- Simple physical laws at microscale translate into complex macroscopic behavior due to nontrivial microstructural interaction

Modeling philosophy in continuum micromechanics:

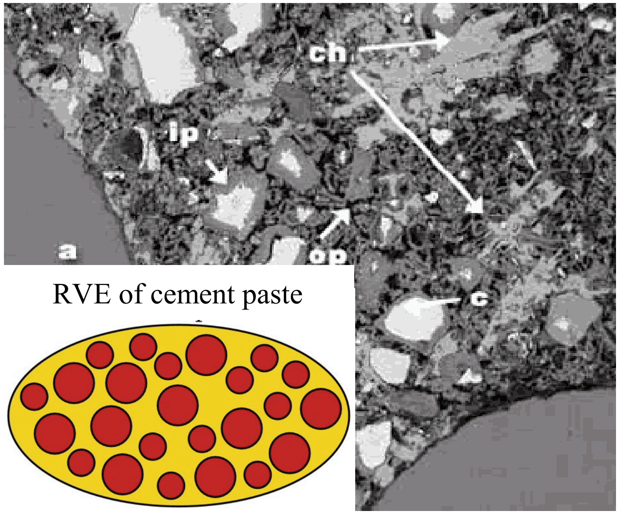
- Introduce as few material constants at microscale as possible
- Upscale to material scale (“homogenization”)
- Identify microscopic material constants from experimental set A
    - All material constants are quantified
    - No fitting parameters !
- Check predictive capabilities by comparing model predictions with results from independent experiment set B

Multiscale modeling: continuum micromechanics

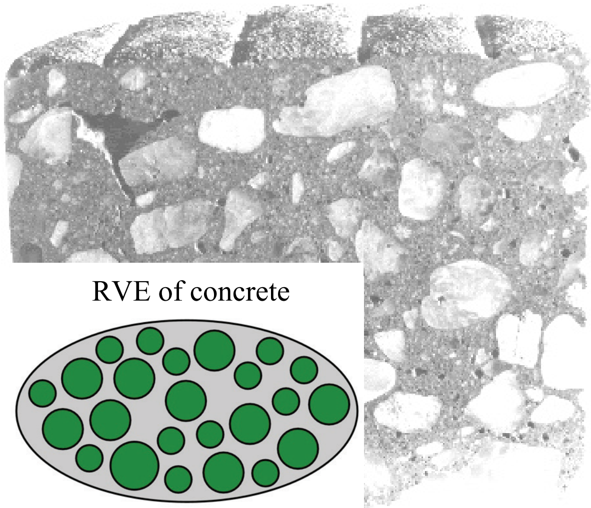
Material phases in scale-separated hierarchical organization



Chatterji and Jeffrey, Nature, 209, 1966



http://www.fhwa.dot.gov



http://www.fhwa.dot.gov

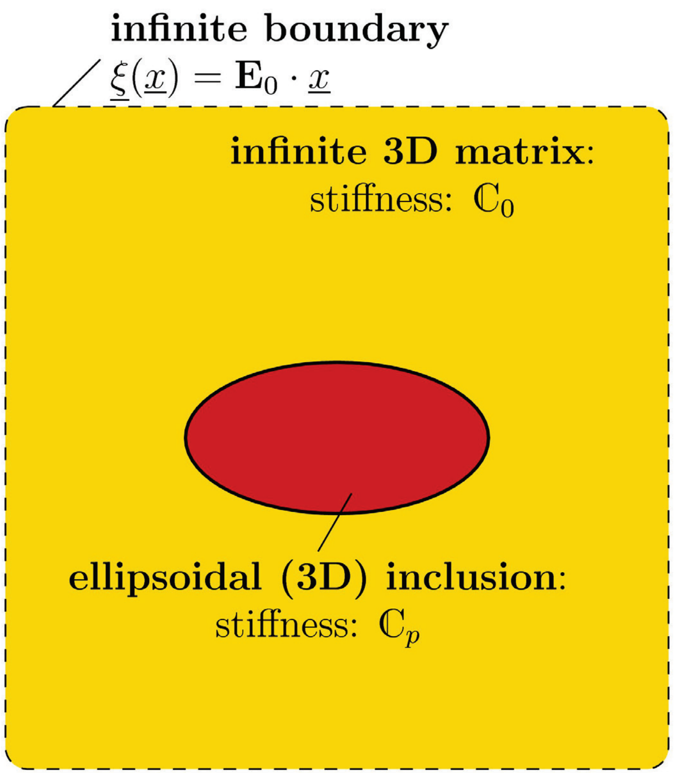
Key properties of material phases

Volume fractions (dosages)
Characteristic shape

Mechanical properties
Interaction

Continuum micromechanics is based on Eshelby-Law problems

= non-trivial three-dimensional strain concentration problem



Uniform remote loading concentrates into uniform strain in inclusion

$$\boldsymbol{\varepsilon}_p = \left[\mathbb{I} + \mathbb{P}_p : (\mathbb{C}_p - \mathbb{C}_0)\right]^{-1} : \mathbf{E}_0$$

Eshelby, Proc.R.Soc.Lond.A. 241, 367-396,1957
Laws, Journal of Elasticity, 7(1), 91-97, 1977

→ use for heterogeneous materials

Loading of infinite matrix is related to loading of RVE (via strain average rule)

Stiffness of infinite matrix is related to stiffness of RVE (according to type of interaction)

Zaoui, Lecture Notes, Ecole Polytechnique, 1997

Zaoui, J.Eng.Mach (ASCE) 128(8), 808-816, 2002

Estimate of homogenized stiffness

$$\mathbb{C}^{hom} = \sum_p f_p \mathbb{C}_p : [\mathbb{I} + \mathbb{P}_p^0 : (\mathbb{C}_p - \mathbb{C}_0)]^{-1} : \left\{ \sum_q f_q [\mathbb{I} + \mathbb{P}_q^0 : (\mathbb{C}_q - \mathbb{C}_0)]^{-1} \right\}^{-1}$$

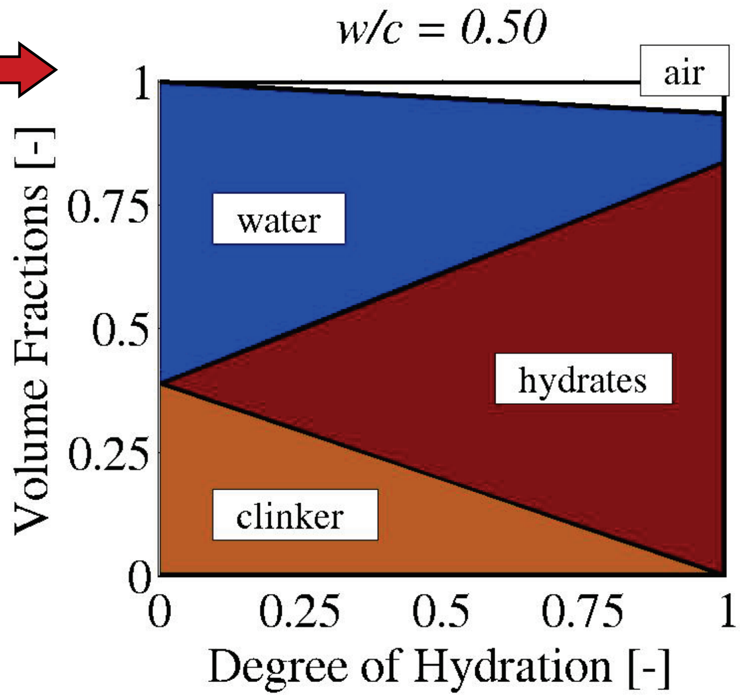
Zaoui, Lecture Notes, Ecole Polytechnique, 1997 Zaoui, J.Eng.Mach (ASCE) 128(8), 808-816, 2002

… accounts for …

- phase volume fractions
- elastic phase stiffnesses (from nanoindentation)
- phase shapes
- phase interaction

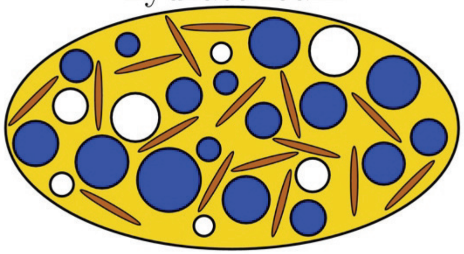
Powers, Brownyard, Res.Lab.Port.Cem.Ass.Bull, 22 101-992, 1948

Acker et al. in Concrete at Early Ages, ACI, 33-48, 1986



Phase volume fractions depend on composition and maturity

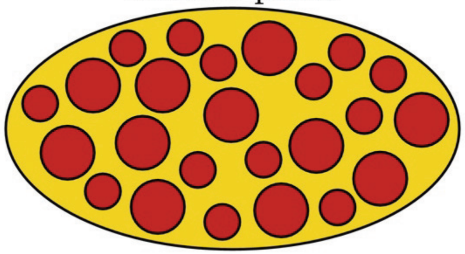
Powers, Brownyard, Res.Lab.Port.Cem.Ass.Bull, 22 101-992, 1948   Acker et al. in Concrete at Early Ages, ACI, 33-48, 1986



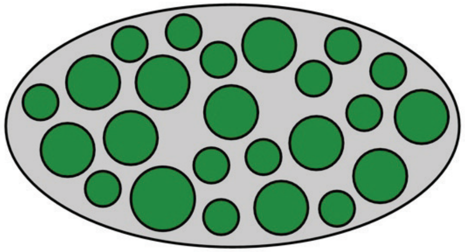
$$\tilde{f}_{hyd} = \frac{f_{hyd}}{1-f_{clin}} = \frac{43.15\,\xi}{20\,\xi + 63\,(w/c)}$$

$$\tilde{f}_{H_2O} = \frac{f_{H_2O}}{1-f_{clin}} = \frac{63\,(w/c) - 26.46\,\xi}{20\,\xi + 63\,(w/c)}$$

$$\tilde{f}_{air} = \frac{f_{air}}{1-f_{clin}} = \frac{3.31\,\xi}{20\,\xi + 63\,(w/c)}$$



$$f_{clin} = \frac{20\,(1-\xi)}{20 + 63\,(w/c)} \qquad f_{hf} = \frac{20\,\xi + 63\,(w/c)}{20 + 63\,(w/c)}$$



$$\bar{f}_{san} = \frac{\frac{s/c}{\rho_{san}}}{\frac{1}{\rho_{clin}} + \frac{w/c}{\rho_{H_2O}} + \frac{s/c}{\rho_{san}}} \qquad \bar{f}_{cp} = 1 - \bar{f}_{san}$$

Isotropic phase elasticity constants

Phase	bulk modulus k [GPa]	shear modulus μ [GPa]
Clinker	$k_{clin} = 116.7$	$\mu_{clin} = 53.8$
Water	$k_{H_2O} = 0.0$	$\mu_{H_2O} = 0.0$
Hydration products	$k_{hyd} = 18.7$	$\mu_{hyd} = 11.8$
Air	$k_{air} = 0.0$	$\mu_{air} = 0.0$
Quartz (sand)	$k_{san} = 37.8$	$\mu_{san} = 44.3$

Acker, Proc.CONCREEP@MIT, 15-26, 2001

Bernard et al. CCR 33 (9) 1293-1309, 2003

Ulm et al. Mat. Struc. 37(1), 43-58, 2004

Pichler and Hellmich CCR 41 (5) 467-476, 2011

$$\mathbb{C}_p = 3k_p\mathbb{J} + 2\mu_p\mathbb{K}$$

Liquid phases in drained conditions

Multiscale modeling of strength of cementitious materials

- Cementitious materials are intact, if deviatoric stress peaks in hydrates < hydrate strength
- Microscopic hydrate failure = macroscopic material strength

$$\max_{\varphi,\vartheta} \overline{\overline{\sigma^{dev}_{hyd,\varphi,\vartheta}}} \leq \sigma^{dev}_{hyd,crit}$$

Scale transition to stress peaks:

via 2nd order stress averages

$$\overline{\overline{\sigma^{dev}_{hyd,\varphi,\vartheta}}} = \sqrt{\frac{-\mu^2_{hyd}}{\varphi_{hyd,\varphi,\vartheta}} \boldsymbol{\Sigma} : \frac{\partial [\mathbb{C}^{hom}]^{-1}}{\partial \mu_{\varphi,\vartheta}} : \boldsymbol{\Sigma}}$$

macroscopic stress

Identification of hydrate strength

- Nanoindentation testing on low-density C-S-H:
  - cohesion c = 50 MPa
  - angle of internal friction φ = 12°

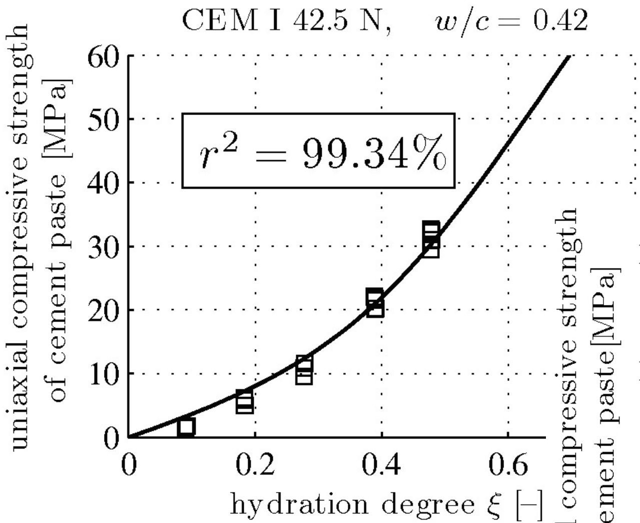
Constantinides and Ulm, MIT Report (2006)
Sarris and Constantinides, CCC (2013)

- This implies:
  - Unaxial compressive strength of hydrates $f_{cu,hyd}$ = 123.5 MPa
  - von Mises-type deviatoric strength $\sigma^{dev}_{hyd,crit}$ = 71.3 MPa

Pichler Hellmich Eberhardsteiner et al. Concreep, (2013)

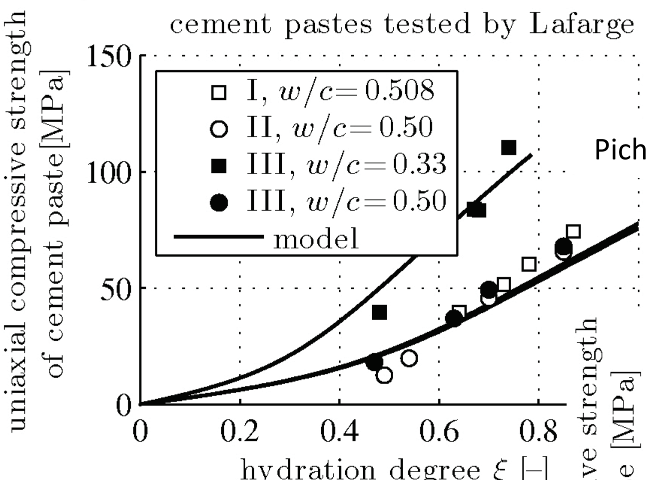
Model validation

Pichler Hellmich Eberhardsteiner et al., Concreep, (2013)



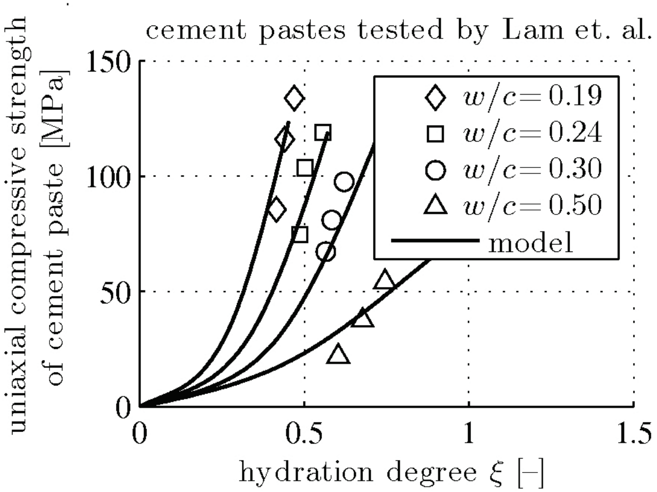
Model vs. tests performed in Vienna

Pichler Hellmich Eberhardsteiner et al., CCR (2013)



... at LCR

Pichler Hellmich Eberhardsteiner et al., CCR (2013)

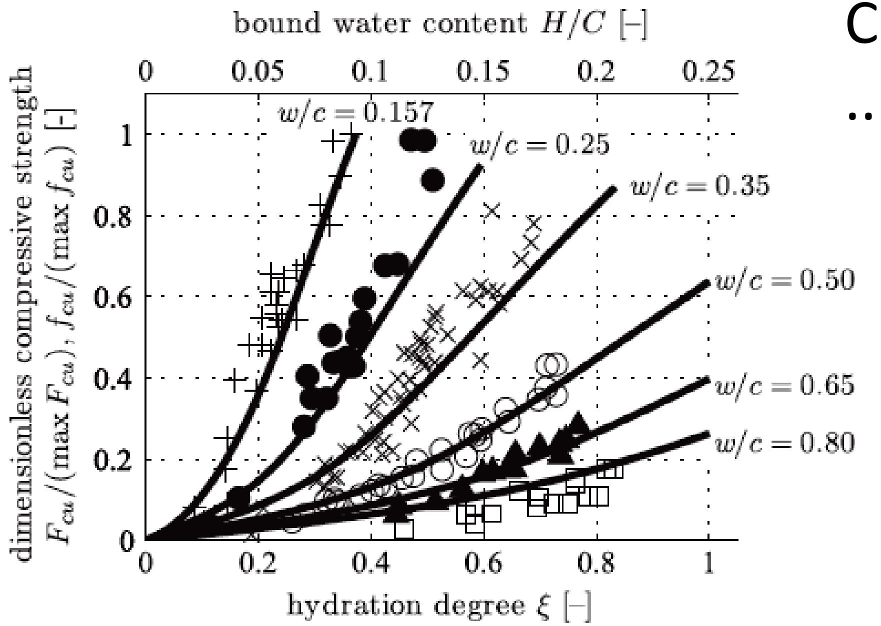


... by Lam et al. CCR (2000)

OPC

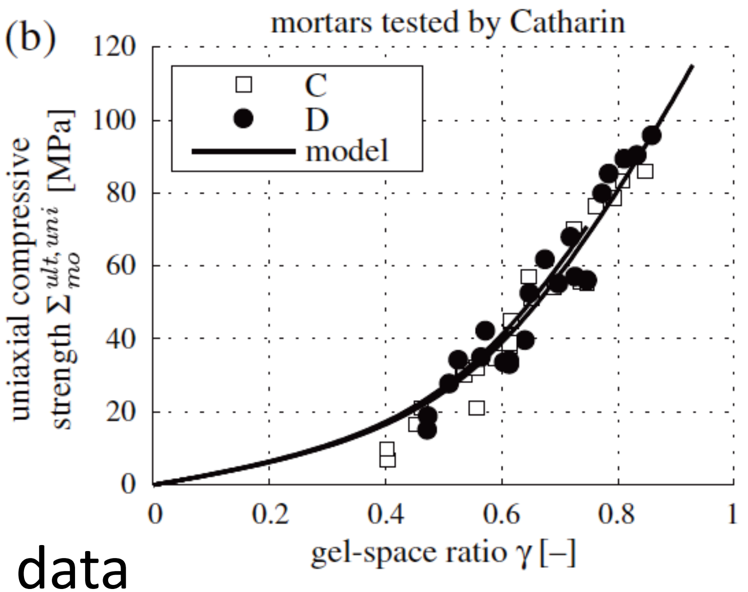
Model validation: continued

Pichler Hellmich, CCR (2011)



Cement paste level
... Taplin (1959) data

Pichler Hellmich Eberhardsteiner et al., CCR (2013)



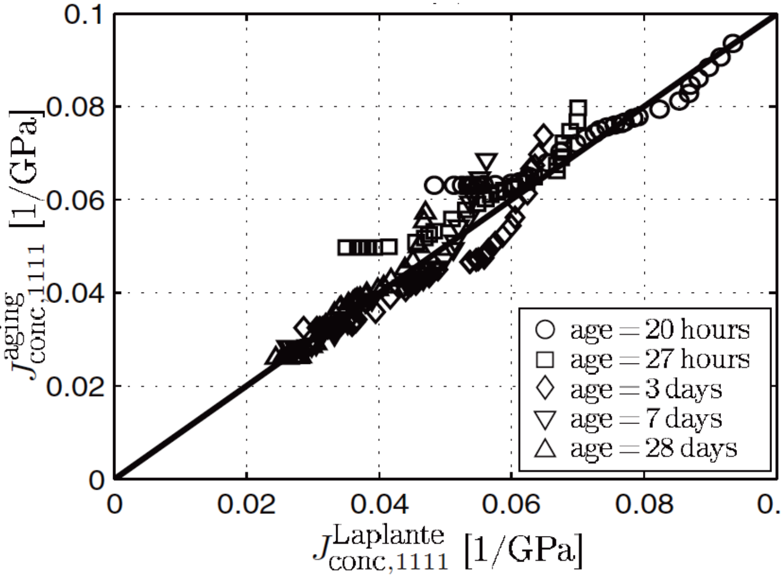
Mortart level
... Catharin (1978) data

Multiscale modeling of creep of cementitious materials

Hydrates: only creeping component of cementitious materials.
Hydrates exhibit deviatoric creep, modeled by Burger's model

Acker, P, Concreep6, 15-25, 2001 Bernard, Ulm, Germaine, CCR, 33(8), 1127-1136. 2003

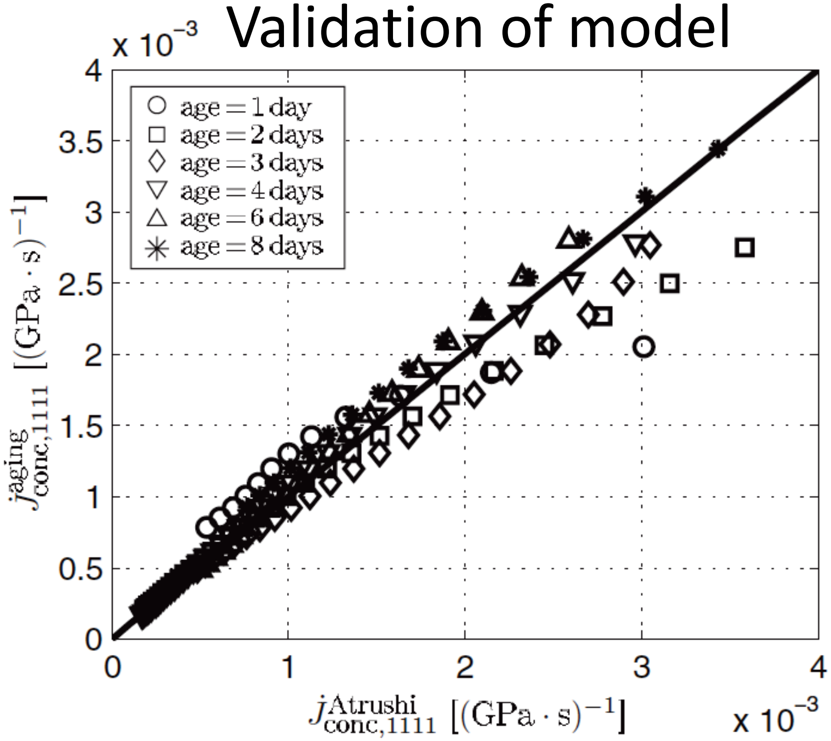
Identification of creep properties



Laplante, P: PhD thesis, ENPC, France , 1993

Scheiner and Hellmich JEngMech, 135(4), 307-323 2009

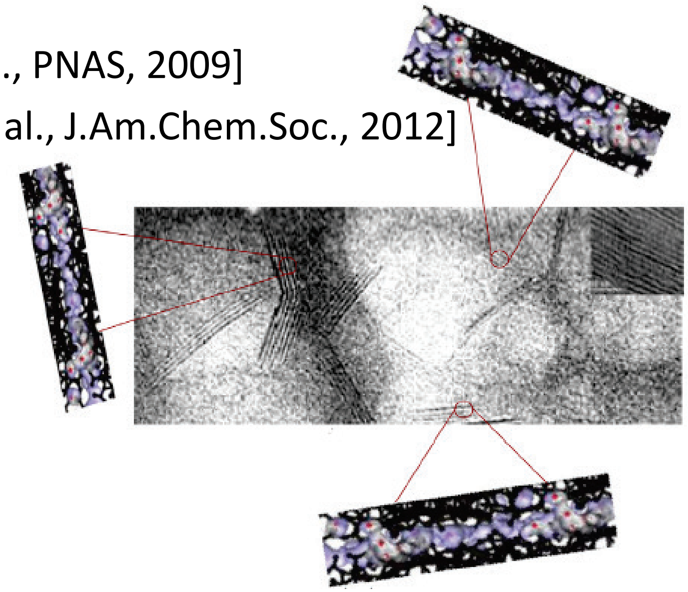
Validation of model



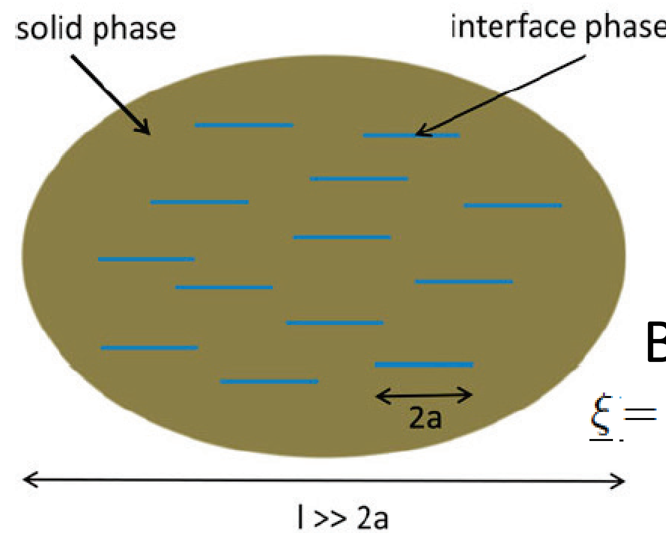
Atrushi, D, PhD thesis, NUST, Norway, 2003

Nanostructure of C-S-H: Parallel interfaces filled by adsorbed water

[Pellenq et al., PNAS, 2009]
[Manzano et al., J.Am.Chem.Soc., 2012]



Modeling: Matrix-interface composite



BC:

$$\underline{\xi} = \underline{\underline{E}} \cdot \underline{x}$$

$$\underline{\underline{E}} = E_{xz} \left(\underline{e}_x \otimes \underline{e}_z + \underline{e}_z \otimes \underline{e}_x \right)$$

Viscous interface behavior:

- No interface opening
- Shear traction proportional to rate of dislocations: $T = \eta^{int} [\![\dot{\xi}]\!]$

[Shahidi Pichler Hellmich, Eur J Mech A/Sol, 2014]

Scale transitions in matrix-interface composite:

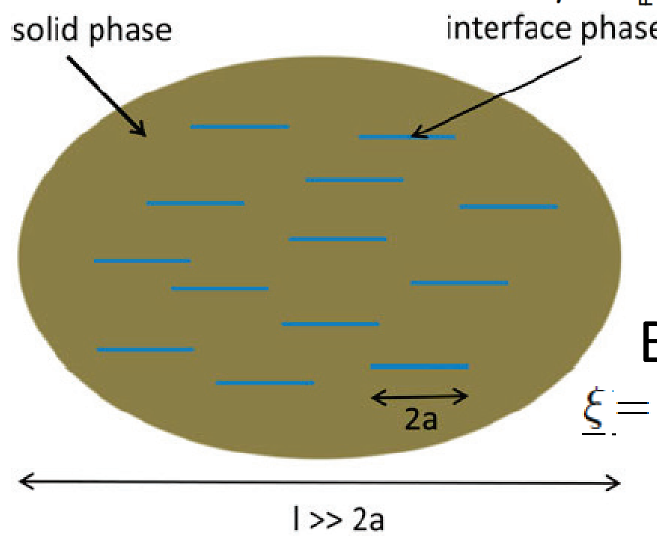
Concentration-influence relations

$$[\![\underline{\xi}]\!] = \underline{\underline{\underline{A}}} : \underline{\underline{E}} + \underline{\underline{D}} \cdot \underline{T}$$

Macroscopic state equations

$$\underline{\underline{\Sigma}} = \underline{\underline{\underline{\underline{C}}}}_{hom} : \underline{\underline{E}} + \underline{\underline{\underline{B}}} \cdot \underline{T}$$

$$T = \eta^{int} [\![\dot{\xi}]\!]$$



BC:

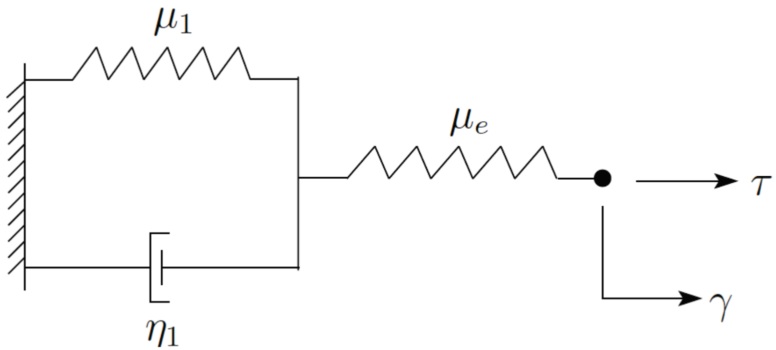
$$\underline{\xi} = \underline{\underline{E}} \cdot \underline{x}$$

Behavior of matrix-interface composite described by differential equation in macrostress and macrostrain

$$\dot{\Sigma}_{xz} \frac{1}{\mu_s} + \Sigma_{xz} \frac{\pi \left[3\,(2-\nu_s) + 16\, d\,(1-\nu_s)\right]}{8\, a\, \eta^{int}\,(1-\nu_s)} = 2\,\dot{E}_{xz} + 2\,E_{xz} \frac{3\,(2-\nu_s)\,\pi\,\mu_s}{8\,(1-\nu_s)\,a\,\eta^{int}}$$

[Shahidi Pichler Hellmich, J Eng Mech (ASCE), In Print.]

Kelvin-Voigt-type Standard Linear Solid Model: [Shahidi Pichler Hellmich, J Eng Mech (ASCE), In Print]



$$\frac{\dot{\tau}}{\mu_e} + \tau\,\frac{\mu_1}{\eta_1}\left(\frac{1}{\mu_1} + \frac{1}{\mu_e}\right) = \dot{\gamma} + \frac{\mu_1}{\eta_1}\,\gamma$$

Behavior of rheological model similar to behavior of matrix-interface composite.

- Identify links by comparing coefficients:

$$\tau = \Sigma_{xz} \qquad \mu_e = \mu_s$$

$$\gamma = 2\,E_{xz} \qquad \mu_1 = \mu_s\,\frac{3\,(2-\nu_s)}{16\,d\,(1-\nu_s)} \qquad \eta_1 = \frac{a\,\eta^{int}}{2\,\pi\,d}$$

Conclusions:

- Continuum micromechanics = powerful tool for homogenization of (hydrating) cementitious materials
- Straightforward extension towards consideration of eigenstresses and/or eigenstrains is based on phase pair influence tensors

  Pichler, Hellmich, J Eng Mech (2010)

- Future outlook: explain creep of cementitious materials by means of shear dislocations of microscopic viscous interfaces

  Shahidi et al., Eur J Mech A/Sol (2014)

  Shahidi et al. J Eng Mech (2015)

Many thanks for your attention

Literature

Multiscale modeling of shotcrete in the framework of NATM safety analysis:

•Hellmich, Mang (2005) Shotcrete elasticity revisited in the framework of continuum micromechanics: from submicron to meter level. Journal for Materials in Civil Engineerig (ASCE) 17(3):246–256.

•Pichler, Scheiner, Hellmich (2008) From micron-sized needle-shaped hydrates to meter-sized shotcrete tunnel shells: Micromechanical upscaling of stiffness and strength of hydrating shotcrete. Acta Geotechnica, 3(4), 273-294.

•Scheiner, Hellmich, C. (2009) Continuum microviscoelasticity model for aging basic creep of early-age concrete. Journal of Engineering Mechanics (ASCE), 135(4), 307–323.

•Ullah, Pichler, Scheiner, Hellmich (2012), Influence of shotcrete composition on load level estimation in NATM tunnel shells: micromechanics-based sensitivity analyses. International Journal for Numerical and Analytical Methods in Geomechanics, 36(9), 1151-1180.

Multiscale modeling of strength of cementitious materials

•Pichler, Hellmich, Eberhardsteiner (2009) Spherical and acicular representation of hydrates in a micromechanical model for cement paste - Prediction of early-age elasticity and strength. Acta Mechanica, 203(3-4), 137-162.

•Pichler, Hellmich (2011) Upscaling quasi-brittle strength of cement paste and mortar: a continuum micromechanics approach. Cement and Concrete Research, 41(5), 467-476.

•Pichler, Hellmich, Eberhardsteiner, Wasserbauer, Termkhajornkit, Barbarulo, Chanvillard (2013) Effect of gel-space ratio and microstructure on strength of hydrating cementitious materials: an engineering micromechanics approach. Cement and Concrete Research, 45, 55-68.

•Pichler, Hellmich, Eberhardsteiner, Wasserbauer, Termkhajornkit, Barbarulo, Chanvillard (2013) The Counteracting Effects of Capillary Porosity and of Unhydrated Clinker Grains on the Macroscopic Strength of Hydrating Cement Paste: A Multiscale Model. Proceedings of the Ninth International Conference on Creep, Shrinkage, and Durability Mechanics of Concrete and Concrete Structures (CONCREEP-9), American Society of Civil Engineers (ASCE), Reston, VA, USA, 2013, ISBN: 978-0-7844-1311-1.

Explanation of macroscopic creep of interfaced materials by slip of viscous microscopic interfaces:

- Shahidi, Pichler, Hellmich (2014): *Viscous Interfaces as Source for Material Creep*: A Continuum Micromechanics Approach. European Journal of Mechanics - A/Solids, 45, 41 - 58.
- Shahidi, Pichler, Hellmich (2015): How Interface Size, Density, and Viscosity Affect Creep and Relaxation Functions of Matrix-Interface Composites -- a Micromechanical Study. Acta Mechanica. In print.
- Shahidi, Pichler, Hellmich (2015): Interfacial Micromechanics Assessment of Classical Rheological Models I: Single Interface Size and Viscosity; *II: Multiple Interface Sizes and Viscosities*. Journal of Engineering Mechanics. In print.
- Qu, Verma, Shahidi, Pichler, Hellmich, Tomar (2015) Mechanics of Organic-Inorganic Biointerfaces - Implications for Strength and Creep Properties. MRS Bulletin, 40, 349 - 358.

Extension of homogenization towards consideration of eigenstrains and/or eigenstresses:

- Pichler, Hellmich (2010) Estimation of Influence Tensors for Eigenstressed Multiphase Elastic Media with Non-Aligned Inclusion Phases of Arbitrary Ellipsoidal Shape. Journal of Engineering Mechanics,136, 1043 - 1053.

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Experimental C-S-H homogenisation scheme

Cyrille Dunant - EPFL, Switzerland
José Granja - Universidade do Minho, Portugal

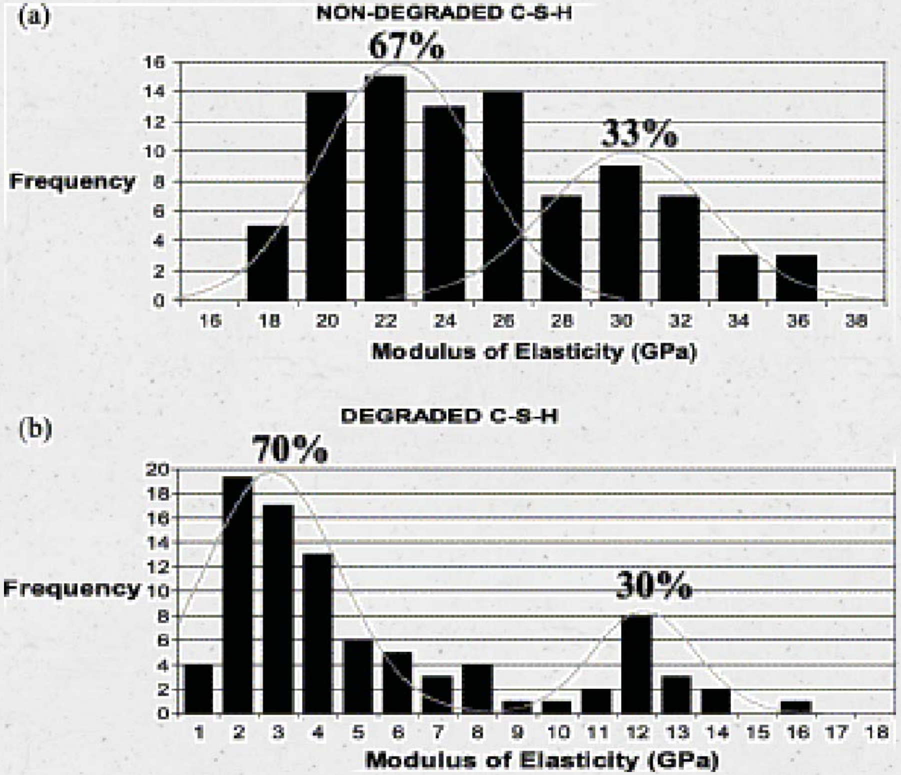
Outline

The State of the Art

The State of the Art

C-S-H properties – Experimentally

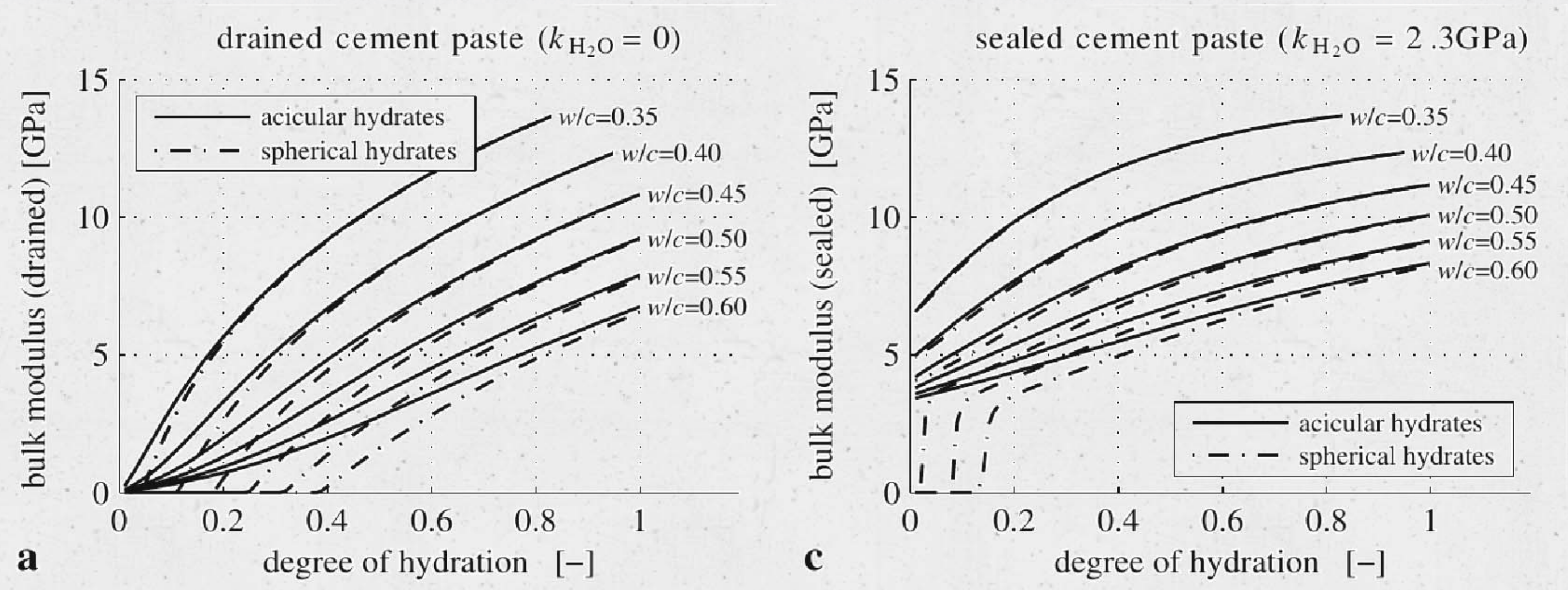
- On mature paste
- On artificial C-S-H
- Need deconvolution
- Back-calculation from homogenisation



1. Constantinides and Ulm, Cem Conc Res, 2004

C-S-H properties — Analytically

- Assume shape
- Assume values from experiment
- Get possible evolution form early age
- Sealed vs drained? Shape?
- valid for $\alpha < 0.5$



1. Pichler et al, Acta Mechanica, 2009
2. Sanahuja et al., Cem Conc Res, 2006

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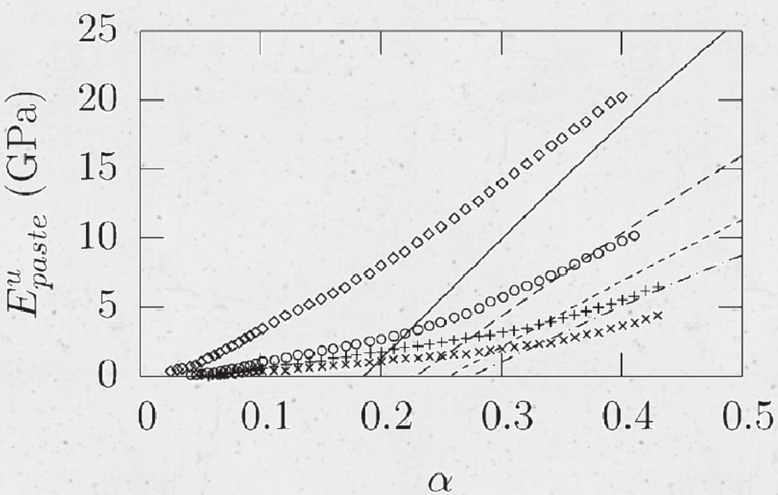

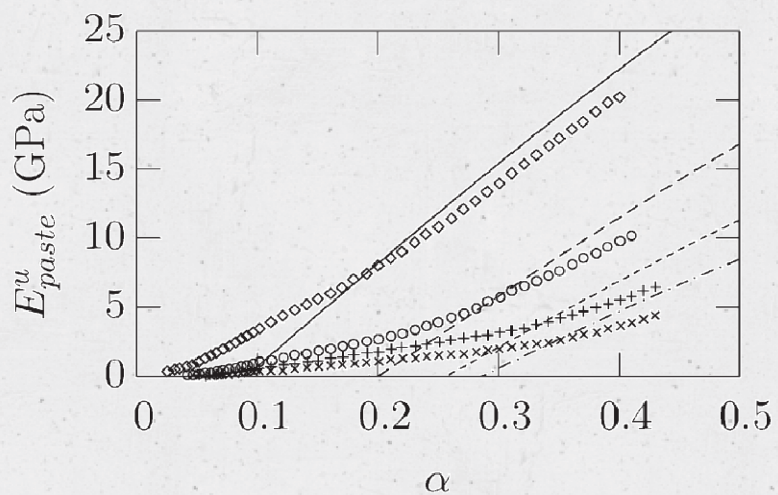

1. Pichler et al, Acta Mechanica, 2009
2. Sanahuja et al., Cem Conc Res, 2006

Requirement for an analytical scheme

- Shape must be known
  - in this case, needles *and* foils, *and* things in between
- Porosity should be known
  - Also the shape of the pores
- Bounds are assumed to be perfect
- Everything should be isotropic

Requirement for an analytical scheme

- Shape must be known
  - in this case, needles *and* foils, *and* things in between
- Porosity should be known
  - Also the shape of the pores
- Bounds are assumed to be perfect
- Everything should be isotropic

All assumption violated

- Needles *and* foils *and* things in between
- Which C-S-H?
- Shape of the pores?

Problems and Objectives

- An analytical scheme is required
- It should relate C-S-H properties to C-S-H porosity
- Experimental values required

Method

- EMM-ARM for paste properties
- ^{1}H NMR for porosity
- μic for the microstructure, AMIE for FE calculations

Experiments

Experiments

EMM-ARM

- E-Modulus Measurement through Ambient Response Method
- Fourier analysis (1822) and beam theory (ca. 1750)
- Modern sensors. . .
- Single unknown is the modulus of the paste

1. Azhenda et al. Cem Conc Res 2012

EMM-ARM

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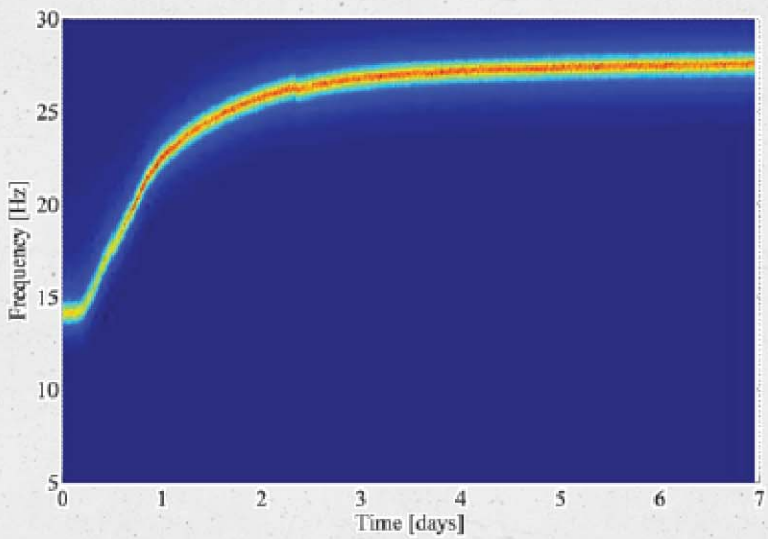
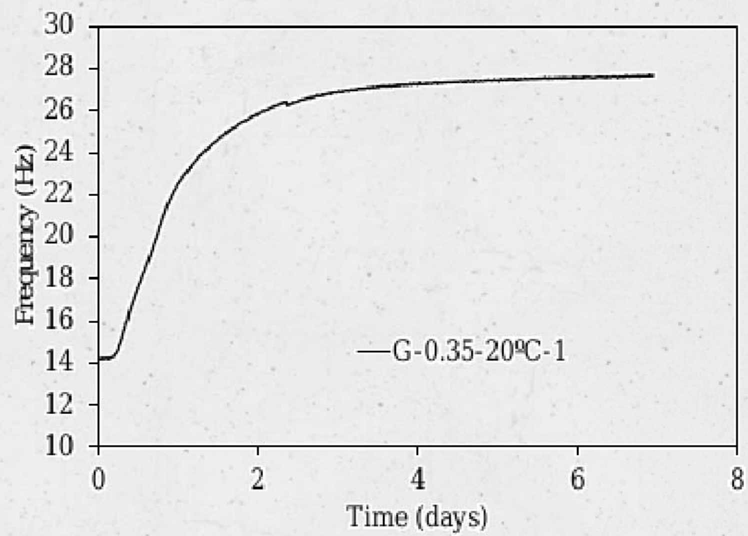


a)

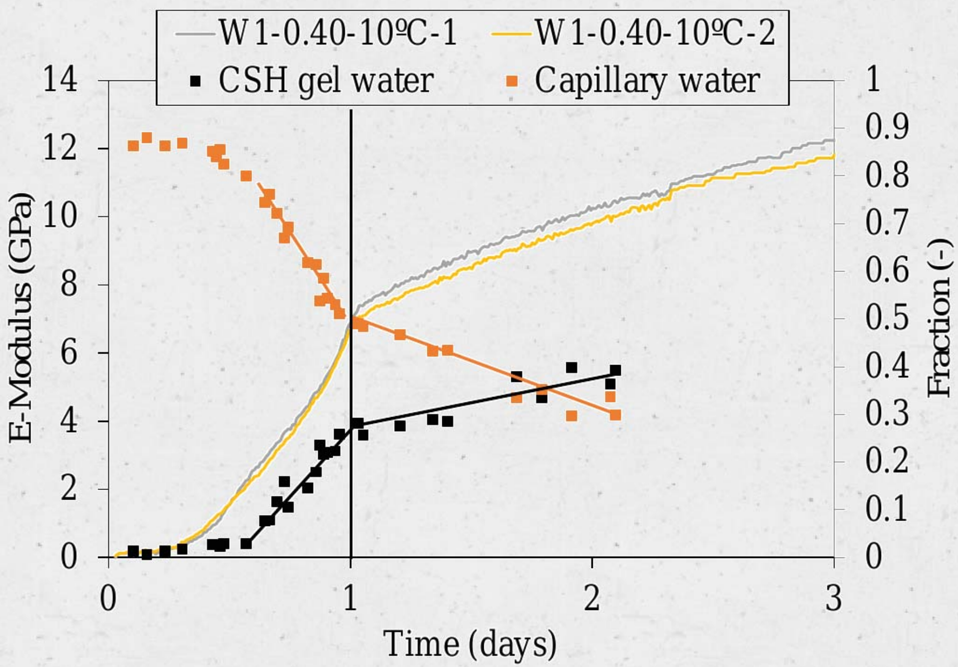


b)

1. Azhenda et al. Cem Conc Res 2012

Results on white cement

- Complements calorimetry/NMR
- Changes in $\frac{dE}{dt}$ reflected in $\frac{dw}{dt}$
- Microstructure?



1. Analysis by A. Muller and J. Granja

Results on white cement

- Complements calorimetry/NMR
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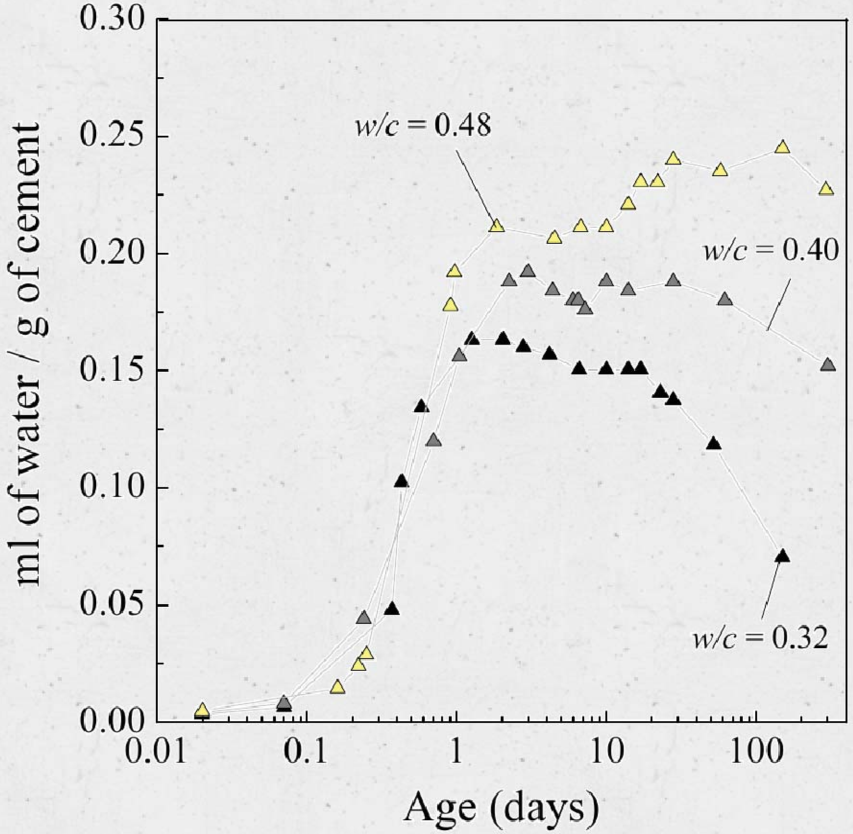
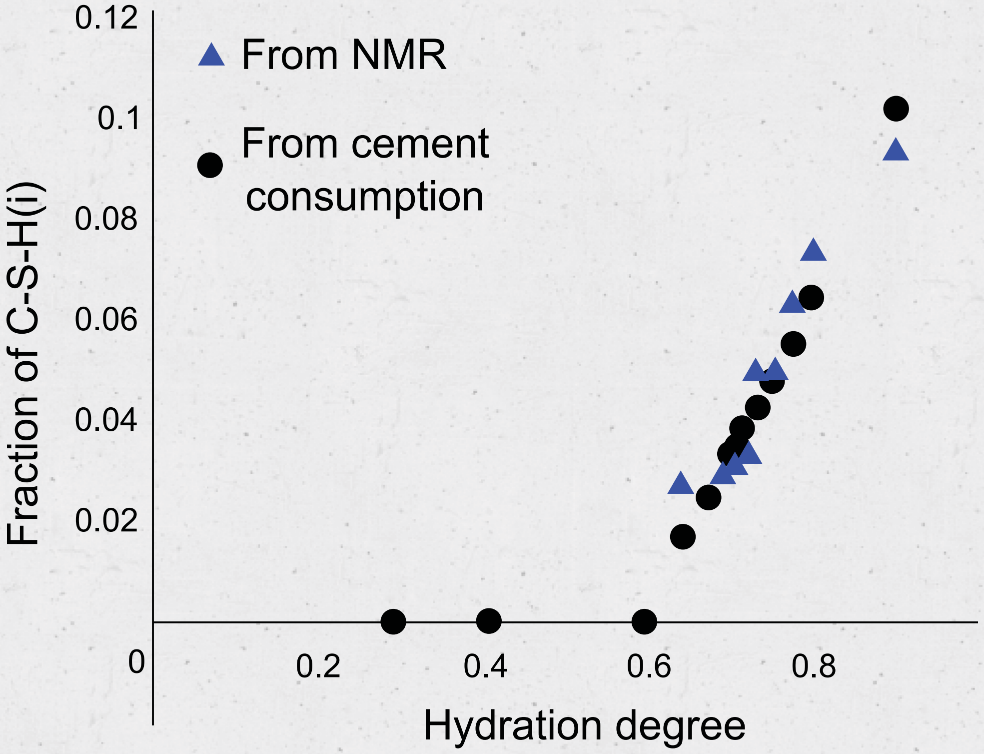


1. Analysis by A. Muller and J. Granja

Finding when inner production starts

- Inner only forms after outer has filled space
- Inner amount can be known from volume of anhydrous
- based on this information, we can construct a model microstructure

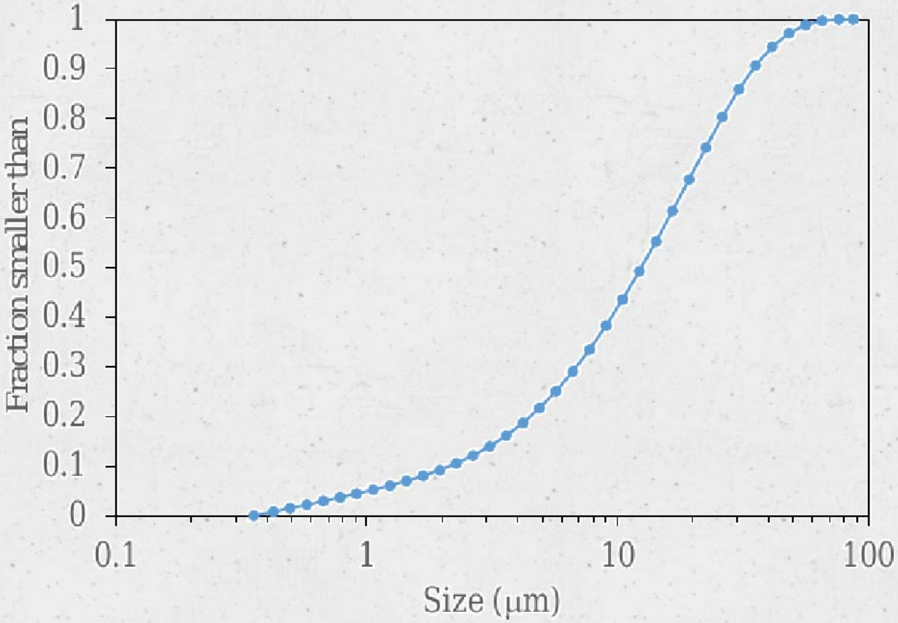


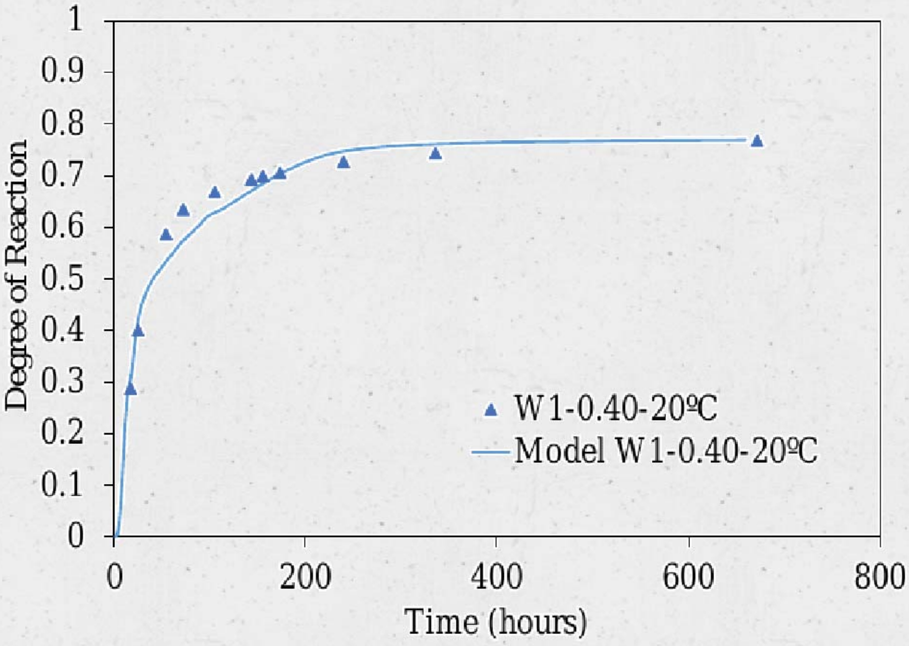
Mic and AMIE Modelling

Mic and AMIE Modelling

Mic Modelling

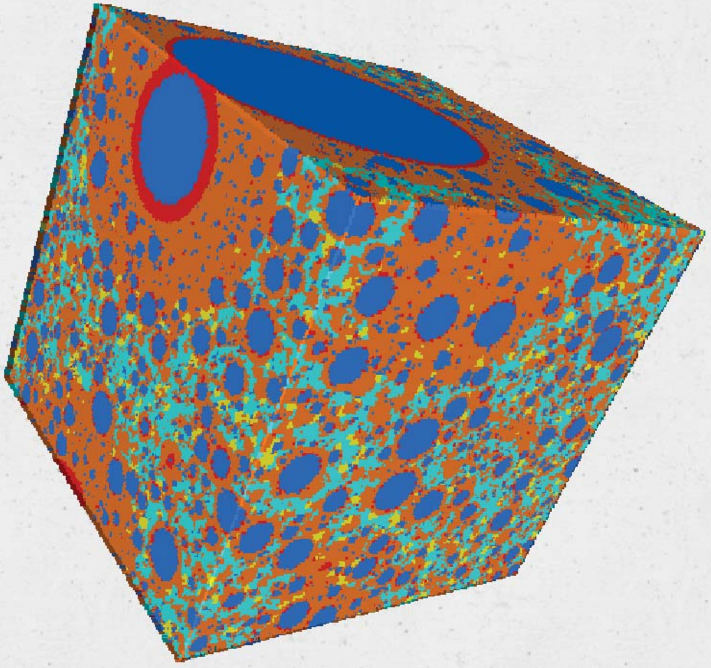
- Parameters fitted to match phase content
- Produce representative microstructures for all α
- μic produces voxel files

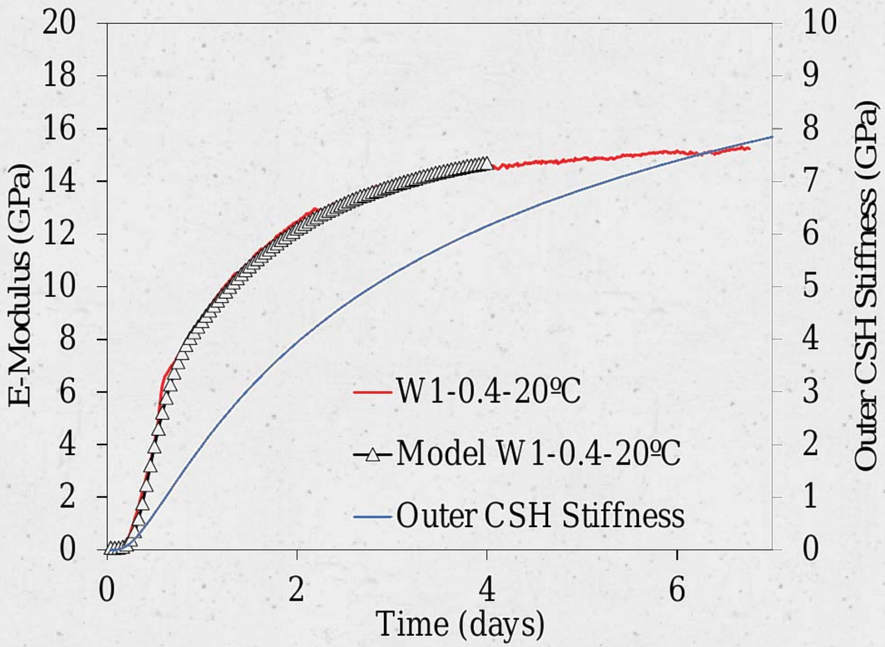




AMIE Setup

- Read the voxel files
- Compute apparent modulus of paste at each step
- Back-calculate modulus of C-S-H to fit paste stiffness (assume ν)

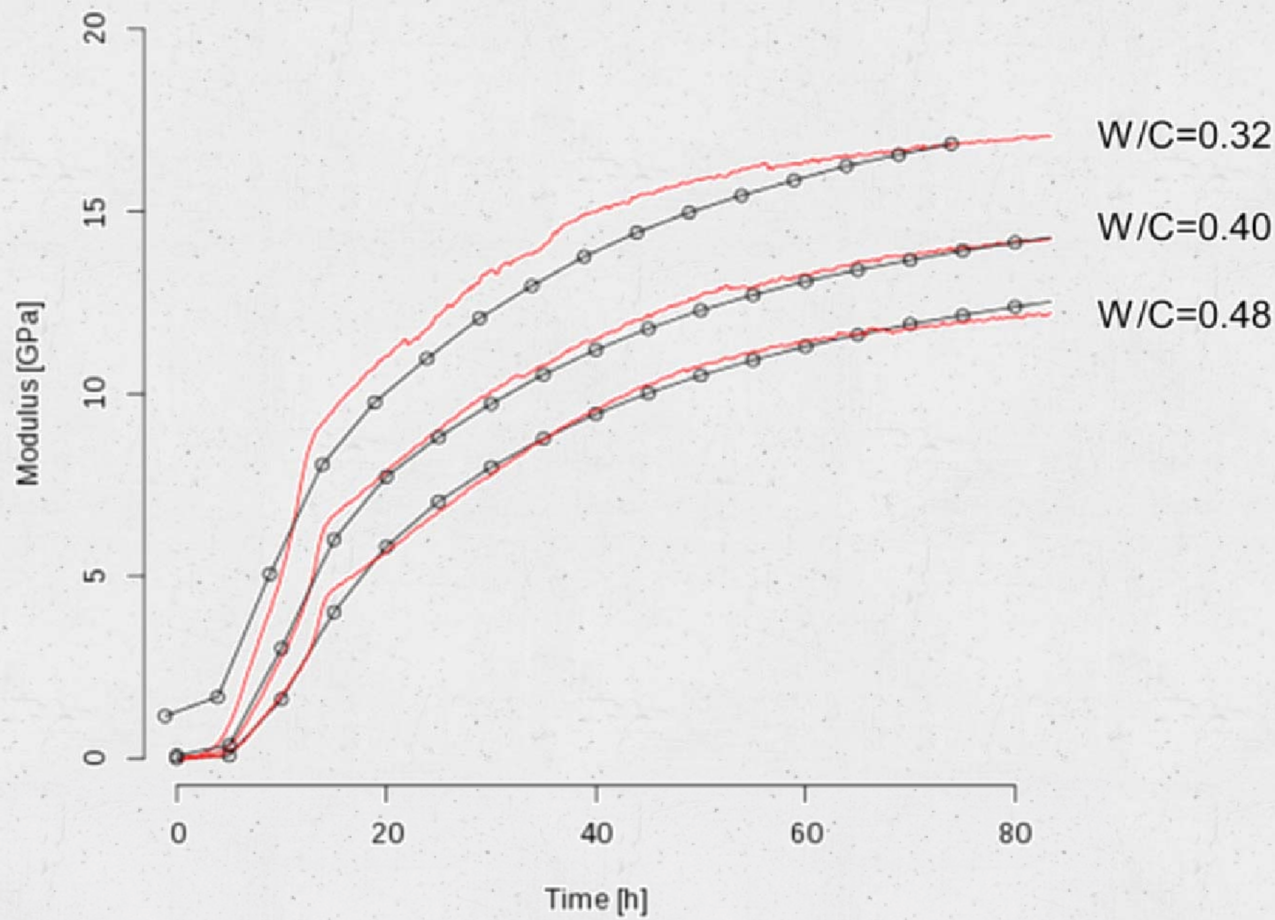




Results and Conclusions

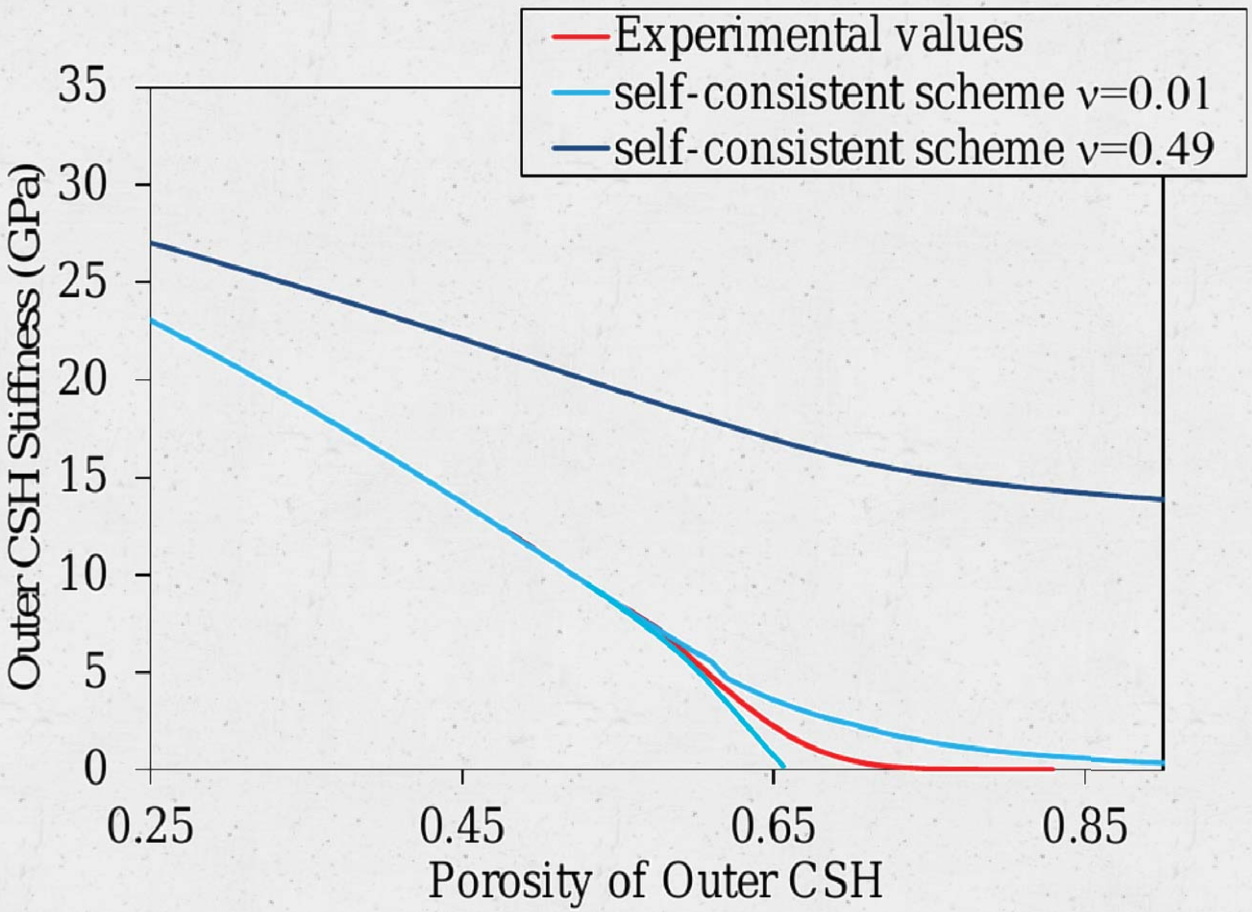
Results and Conclusions

Experiments vs simulations



Single $E(\phi)$ relationship.

Relating to published results



This setup behaves as though it was drained, and lies clearly between spheres and needles.

Conclusions

- Produce an empirically measured homogenisation scheme for C-S-H
- Need to also take into account ν
- Need to extend the approach to other systems
  - promising results: the value derived here for white cement were found to work well for grey cement mixes

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Multiscale modeling of concrete

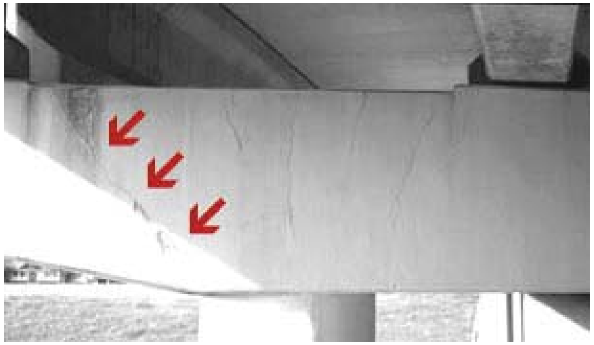
From Mesoscale to macroscale

Jörg F. Unger

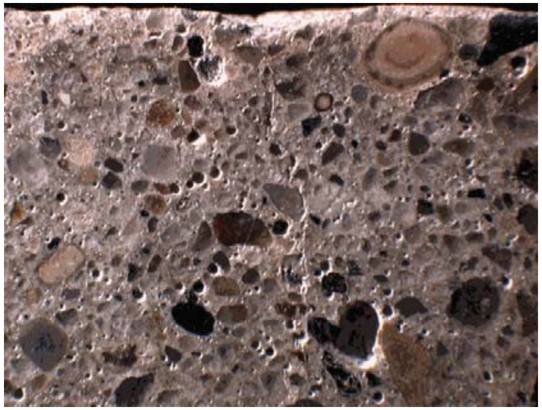
Federal Institute for Materials Research and Testing, Germany

Vienna - 2015/09/19

Motivation







Outline

Modeling mesoscale geometries

Discretization

Constitutive models for concrete

Multiscale models

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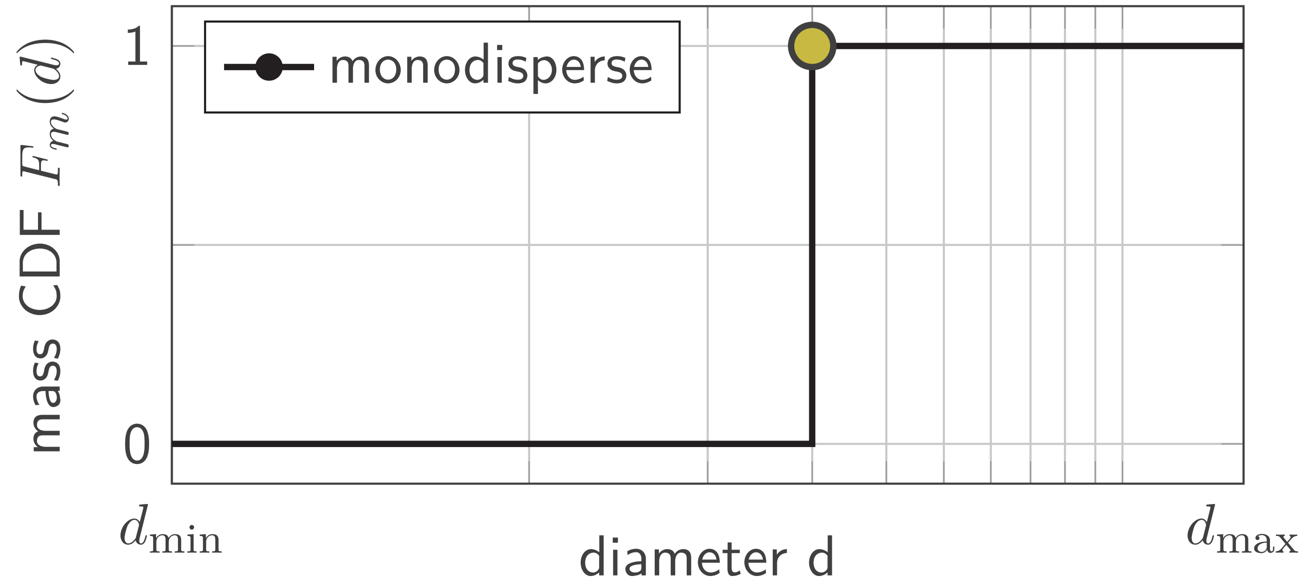
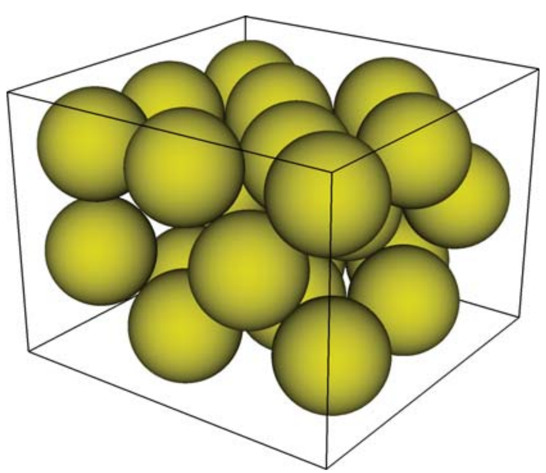
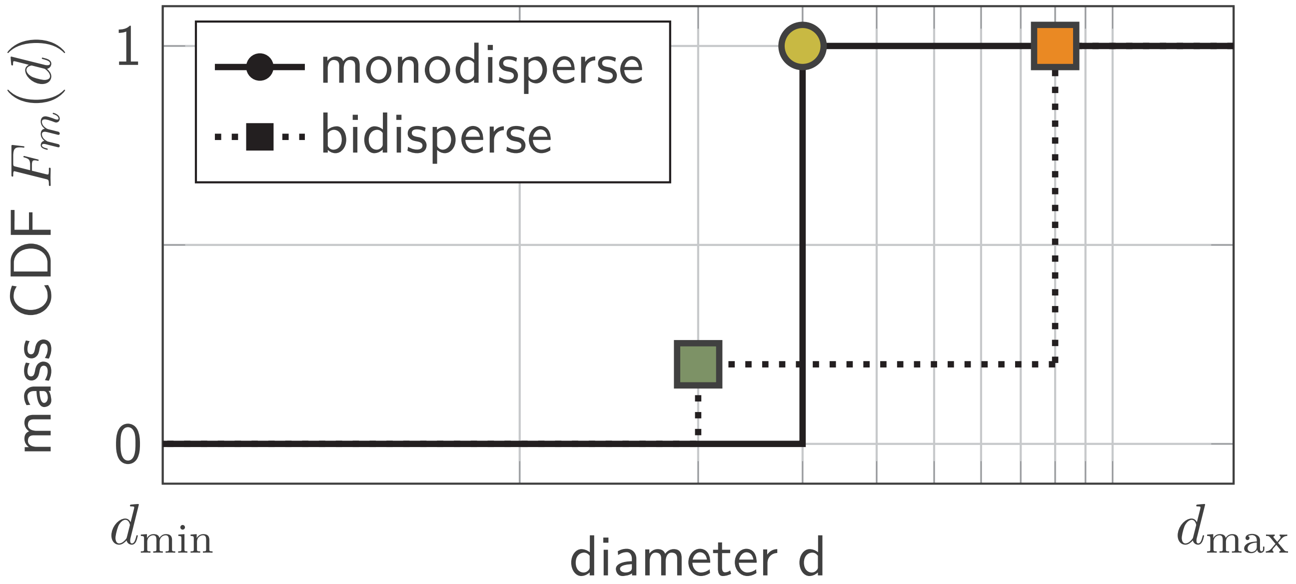
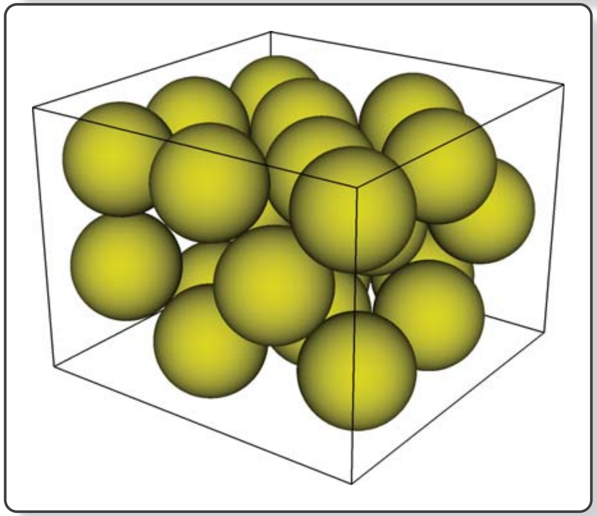
Grading curve

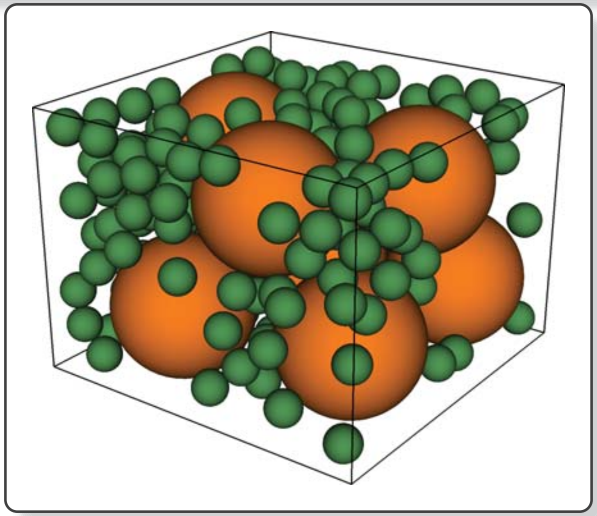




Grading curve







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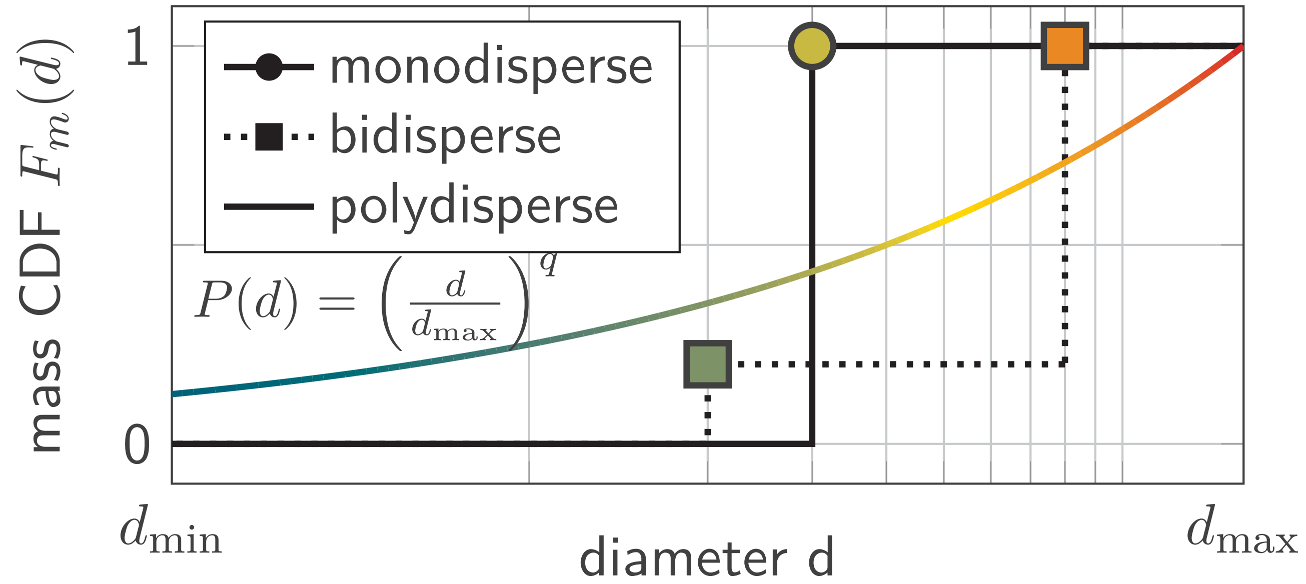

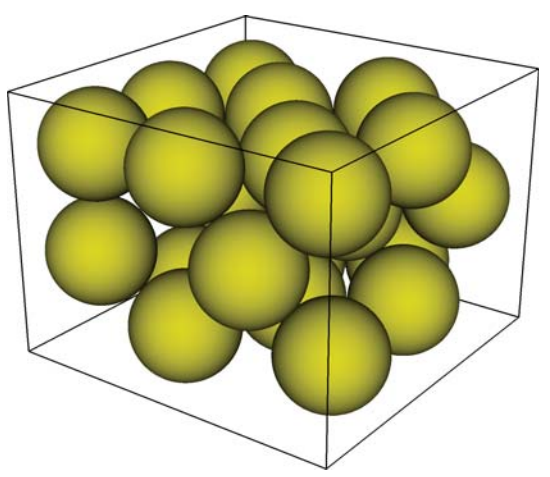

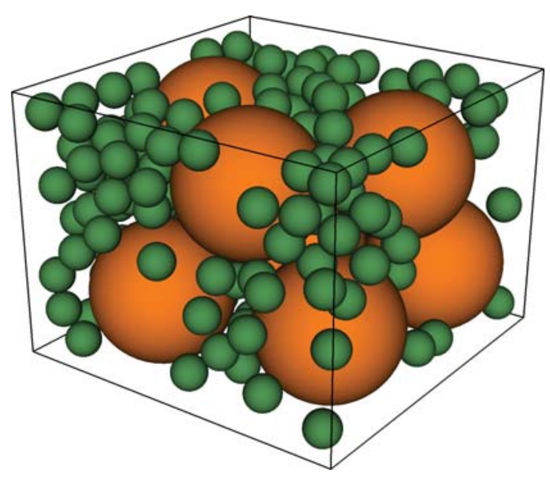

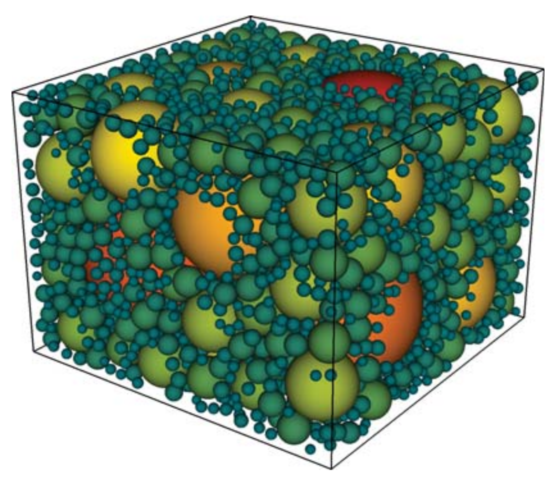

Mesoscale modeling of concrete

RSA

- random sequential addition
- very efficient at low ϕ

Mesoscale modeling of concrete

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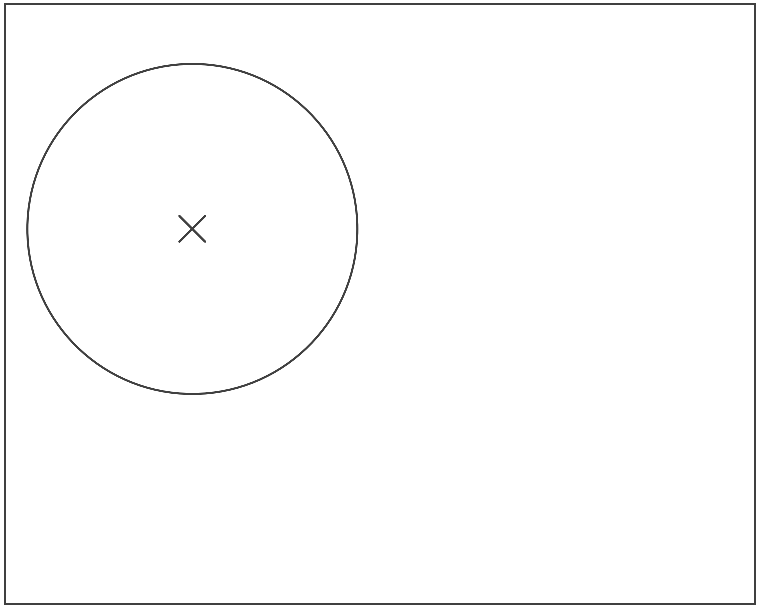

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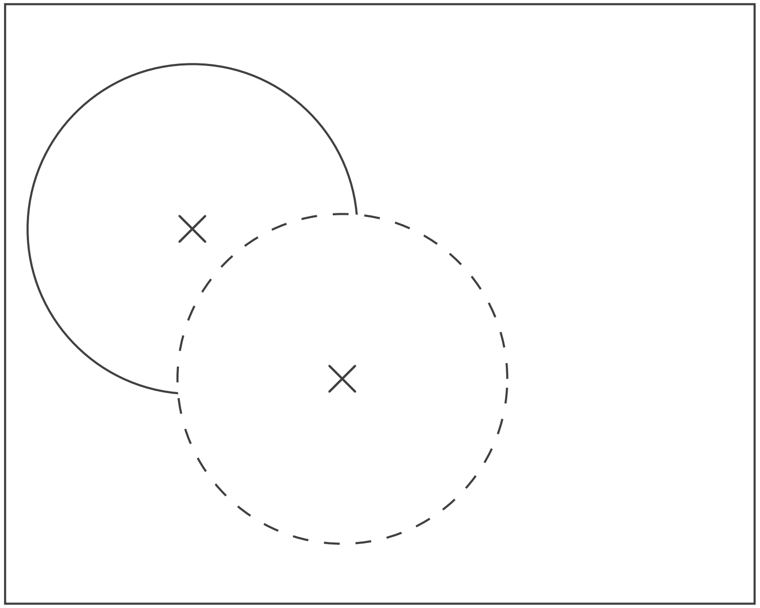

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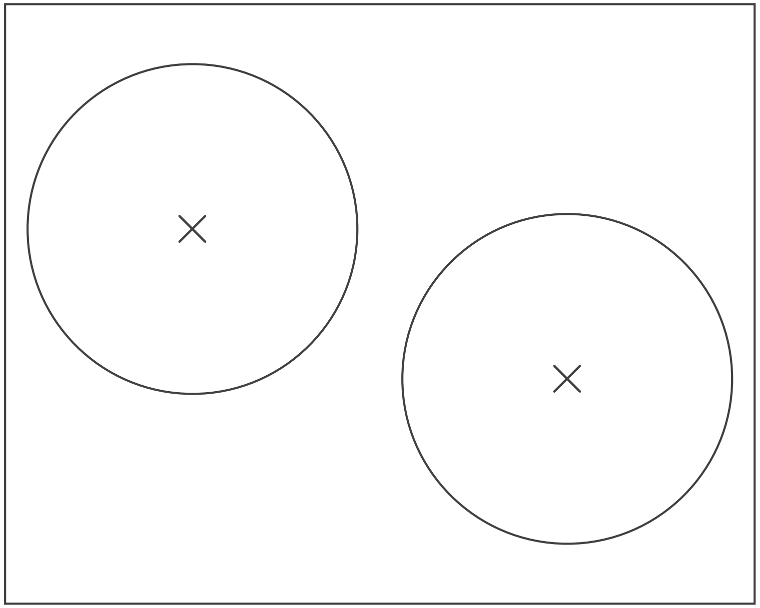

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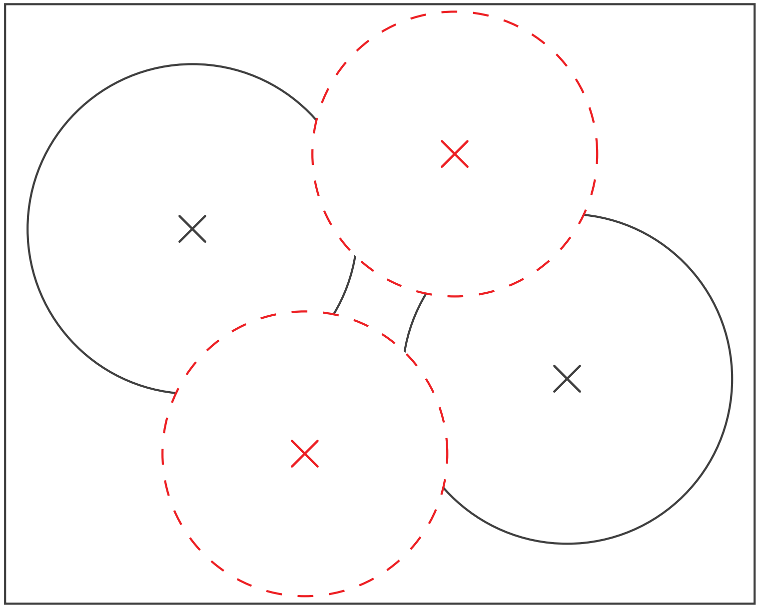

- fixed black particles block red particles

Mesoscale modeling of concrete

RSA

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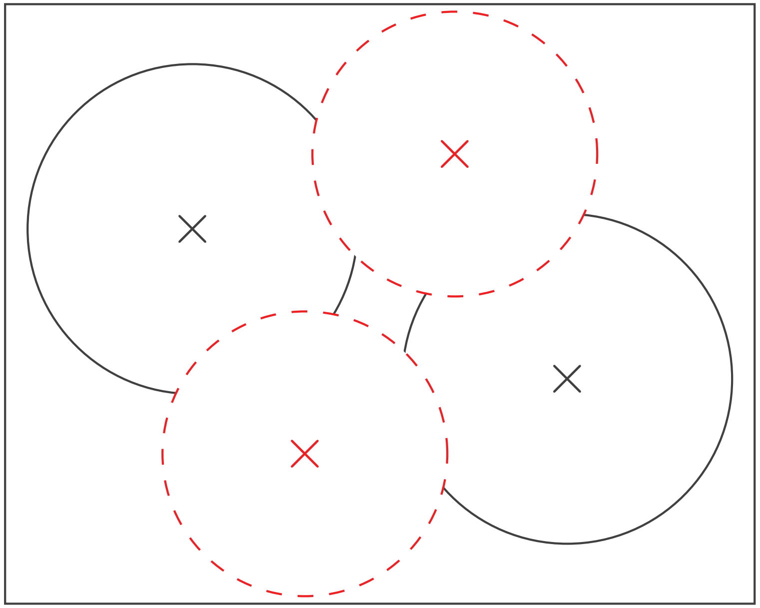
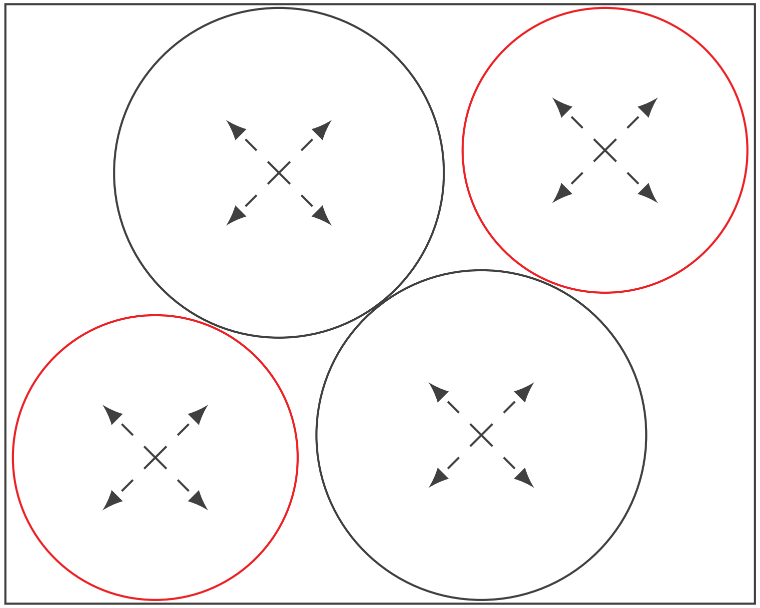


- fixed black particles block red particles

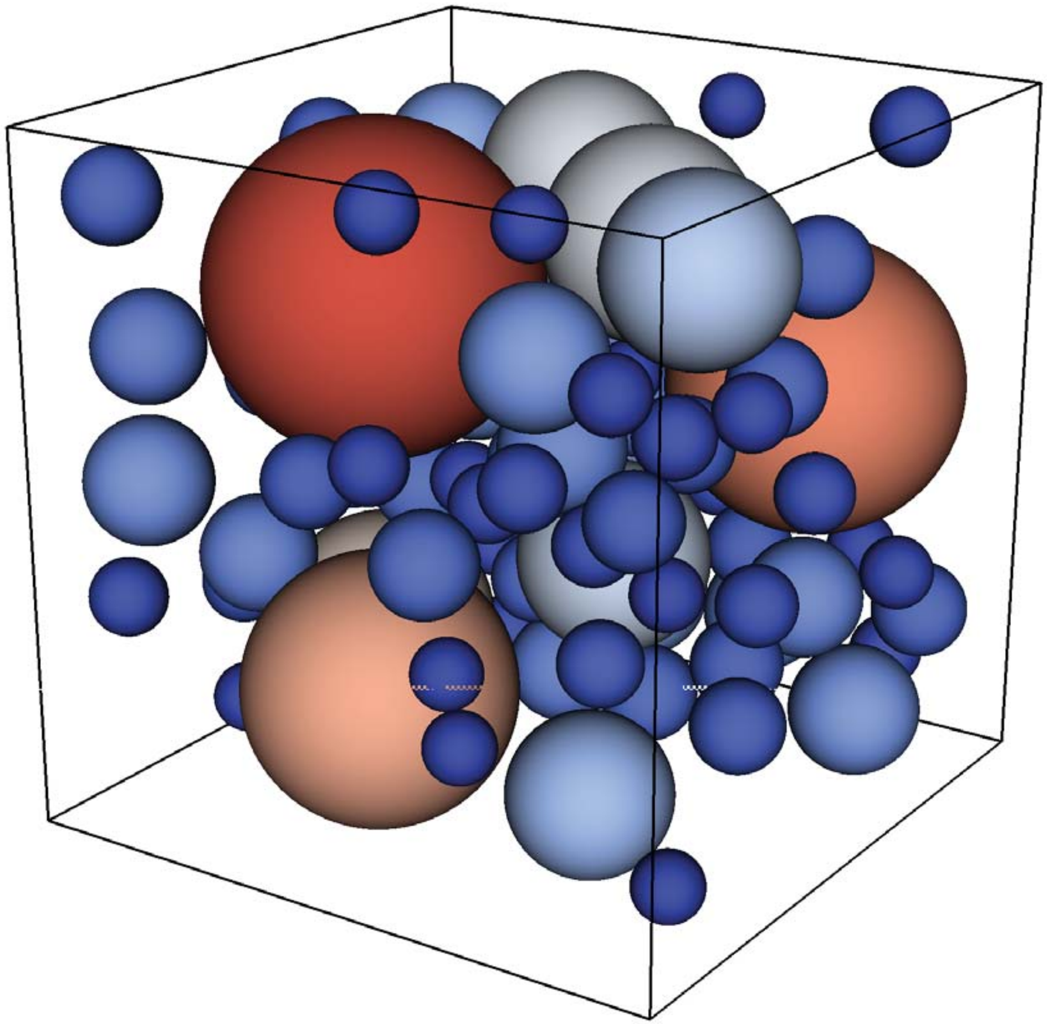
EDMD

- event-driven molecular dynamics
- able to reach jammed packings



- movable particles allow rearrangement

Example



Further information:[Titscher and Unger, 2015]

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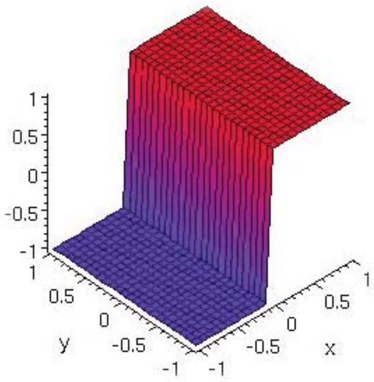
eXtended Finite Element Method(XFEM)

Displacement interpolation

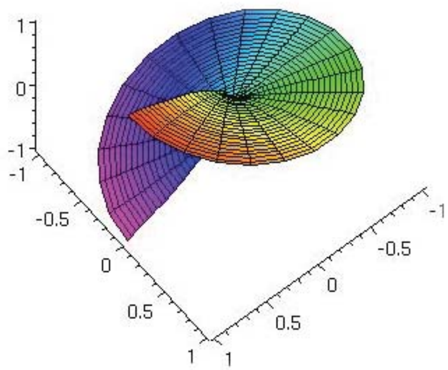
$$\mathbf{d}(\mathbf{x}) = \sum_{i=1}^{N_{tot}} \phi_{i,std}(\mathbf{x}) d_{i,std} + \sum_{j=0}^{N_{enr}} \Psi(\mathbf{x}) \phi_{j,enr}(\mathbf{x}) d_{j,enr}$$

$\phi_{i,std}$	standard shape functions
$\phi_{i,enr}$	enriched shape functions

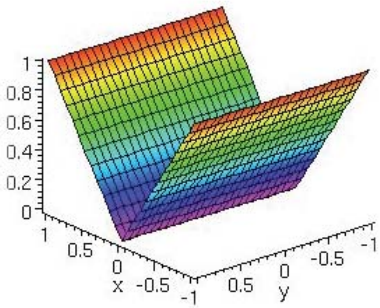
Enrichment function Ψ



Heaviside



cracktip

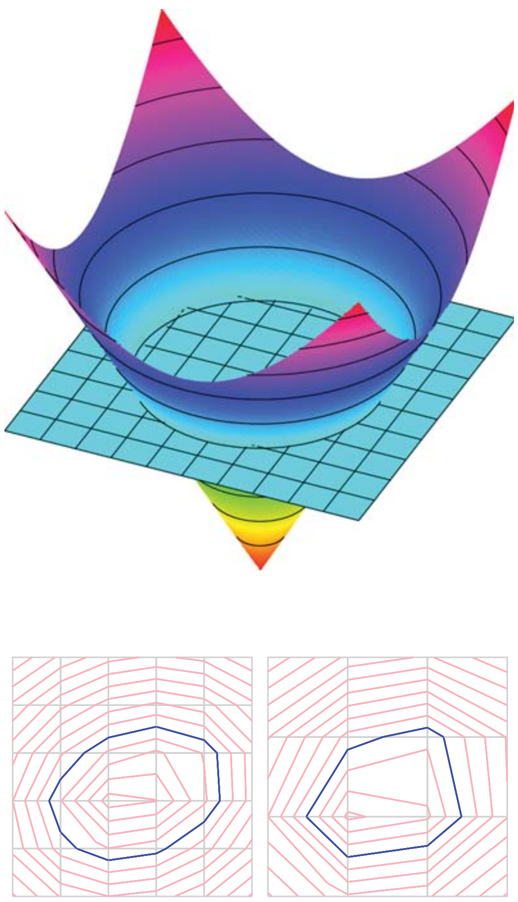


distance function

[Unger et al., 2007]

Levelsets as enrichment for material interfaces

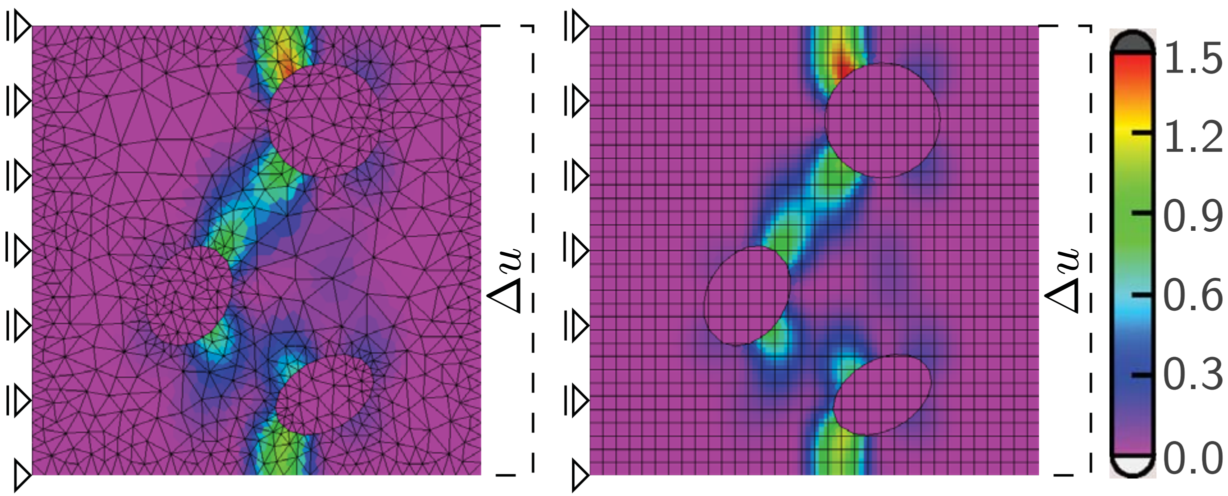
Levelset function



XFEM enrichment

- enrichment function $\psi = |d(\mathbf{x})|$ with
  d : signed distance function
- function $d(\mathbf{x})$ approximated using FE-shape functions

Damage distribution at the peak load in [%]



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Constitutive models for concrete

Combined damage-plasticity model [Unger et al., 2011]

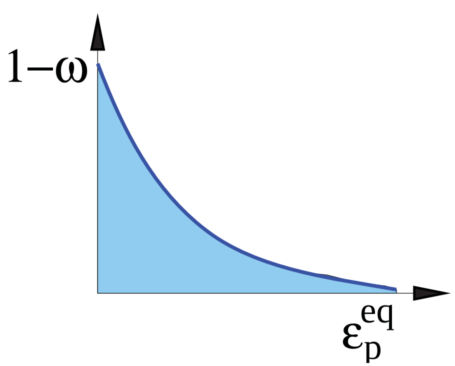
- evolution of stresses

$$\boldsymbol{\sigma} = (1-\omega)\boldsymbol{D}\,(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\boldsymbol{p}})$$

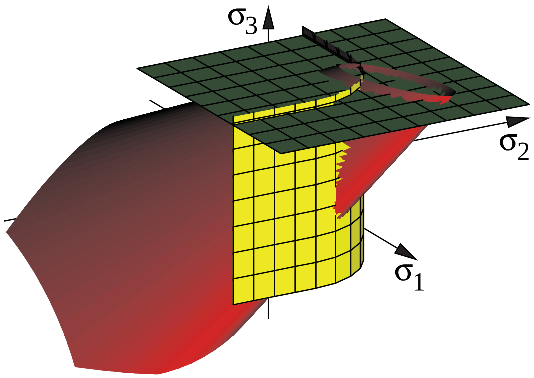
- combination of Drucker-Prager and Rankine yield surfaces
- damage evolution driven by nonlocal equivalente plastic strain

$$\omega = 1 - e^{-\frac{\tilde{\kappa}}{\kappa_d}} \qquad \kappa_d = f(G, f_{ct}, R)$$

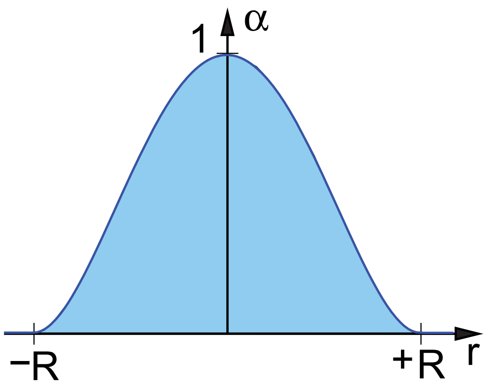
Damage



Yield surfaces



Weighting function



Gradient enhanced damage model

Governing equations

$$\nabla \cdot \boldsymbol{\sigma} = \mathbf{0} \quad \text{with} \quad \boldsymbol{\sigma} = (1 - \omega(\bar{\varepsilon}_{\text{eq}}))\boldsymbol{C}\boldsymbol{\varepsilon}$$

$$\bar{\varepsilon}_{\text{eq}} - c\nabla^2\bar{\varepsilon}_{\text{eq}} = \varepsilon_{\text{eq}} \quad \text{with} \quad \varepsilon_{\text{eq}} = \varepsilon_{\text{eq}}(\boldsymbol{\varepsilon})$$

Damage evolution via history variable κ

$$\omega = \omega(\kappa), \quad \dot{\kappa} \geq 0, \quad \bar{\varepsilon}_{\text{eq}} - \kappa \leq 0, \quad \dot{\kappa}(\bar{\varepsilon}_{\text{eq}} - \kappa) = 0$$

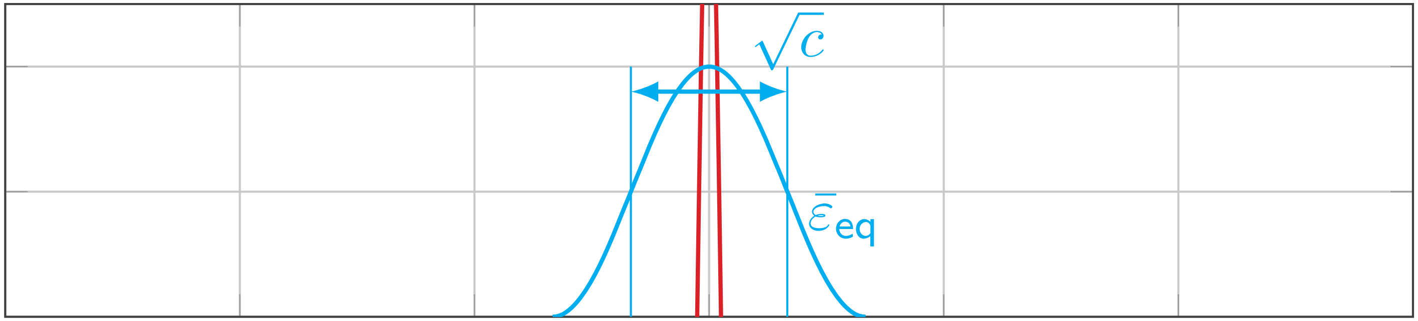
Boundary conditions

- displacements

$$\boldsymbol{d}(\boldsymbol{x}_\Gamma) = \boldsymbol{d}_\Gamma$$

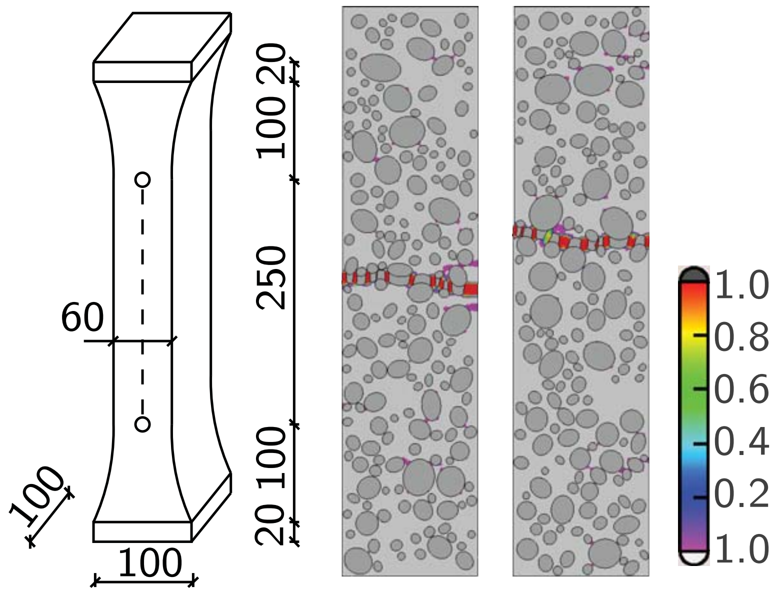
- non-local equivalent strains

$$\nabla\bar{\varepsilon}_{\text{eq}}(x_\Gamma) \cdot \boldsymbol{n}(x_\Gamma) = 0$$

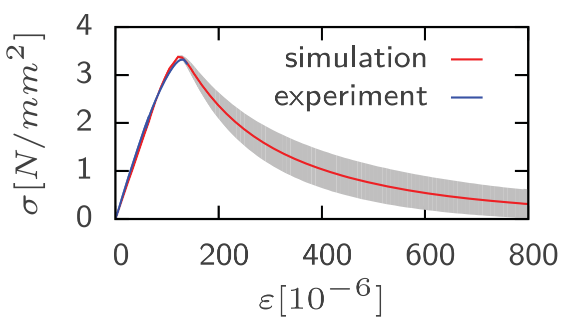


Stochastic character of concrete

Damage distribution



Stress-strain curve

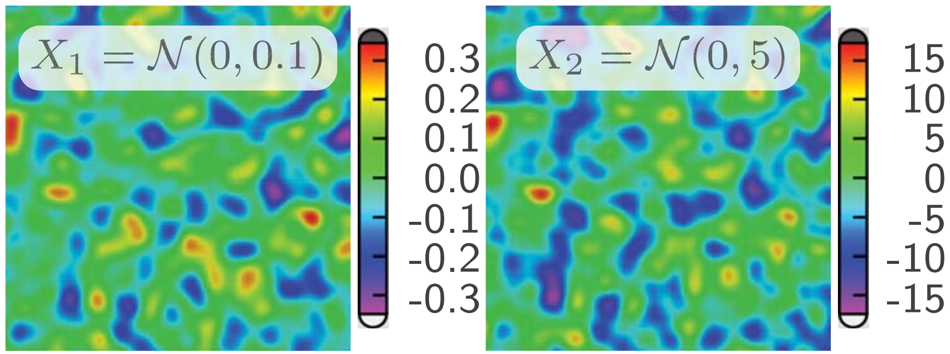


Causes of stochastic behaviorg

- heterogenous material structure
- random distribution of material parameters

Correlated random field

- $P_i(\boldsymbol{x}) = [1 + X_i(\boldsymbol{x})]\,\bar{P}$
- $\rho_{12} = 0.8, l_{corr}$=5cm, 100x100cm



- efficient implementation using series expansion and FFT

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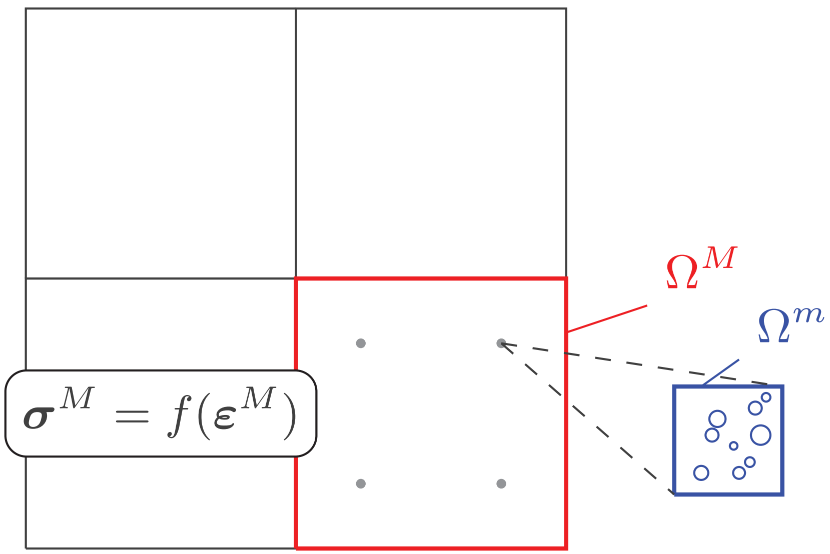
Coupled hierarchical multiscale model

General procedure for FE^2-type of methods

- apply macro strain as boundary condition to the fine scale
- solve fine scale problem
- pass back average stress and algorithmic stiffness to macro scale

Macroscale IP with attached fine scale



Features

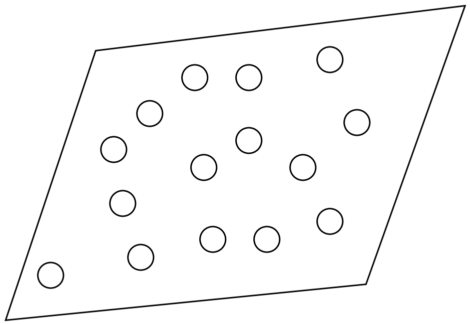
- can bridge multiple scales
- simulates real physics
- high computational effort
- unable to represent localization on fine scale
- requires Representative Volume Elements (RVE)

Hill-Mandel lemma - standard approach

Energy equivalence

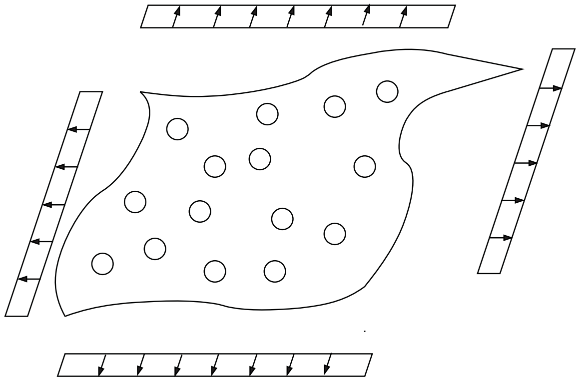
$$\tilde{\boldsymbol{\sigma}}\delta\tilde{\boldsymbol{\epsilon}} = \frac{1}{V}\int_\Omega \boldsymbol{\sigma}(\boldsymbol{x})\delta\boldsymbol{\epsilon}(\boldsymbol{x})\, d\Omega$$

displacements



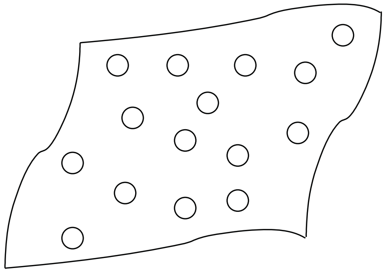
- $\boldsymbol{d} = \boldsymbol{\varepsilon}^M \boldsymbol{X}$
- prevents localization at the boundary
- generally too stiff

forces



- implementation using constraint $\boldsymbol{\varepsilon}^M - \tilde{\boldsymbol{\varepsilon}} = 0$
- spurious localization at single nodes
- generally too soft

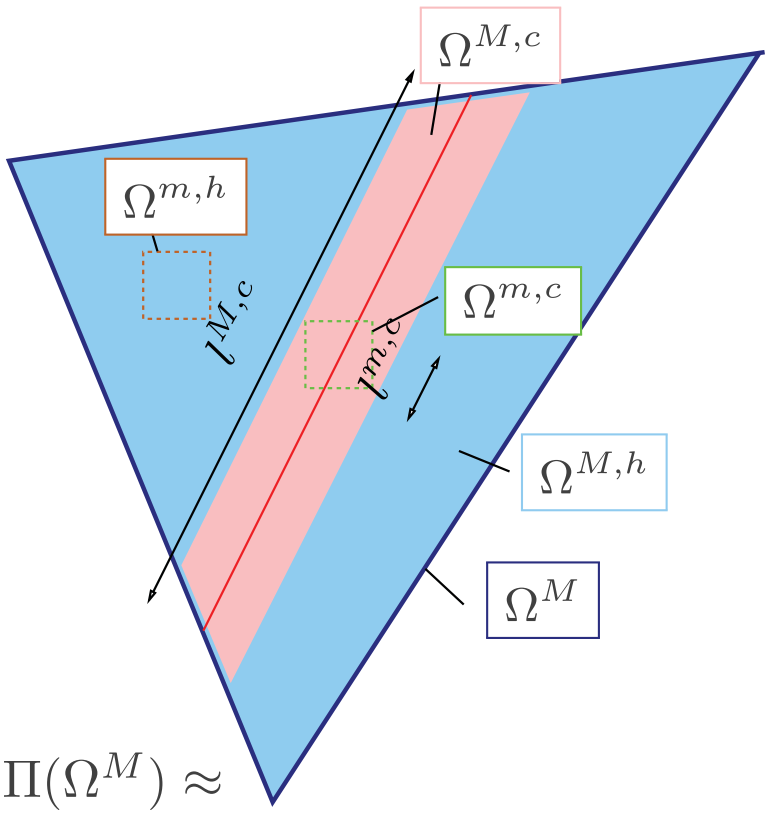
periodic displacements



- $\boldsymbol{d}^r = \boldsymbol{d}^l + \boldsymbol{\varepsilon}^M(\boldsymbol{X}^l - \boldsymbol{X}^r)$
- $\boldsymbol{d}^t = \boldsymbol{d}^b + \boldsymbol{\varepsilon}^M(\boldsymbol{X}^b - \boldsymbol{X}^t)$
- localization only for vertical/horizontal crack

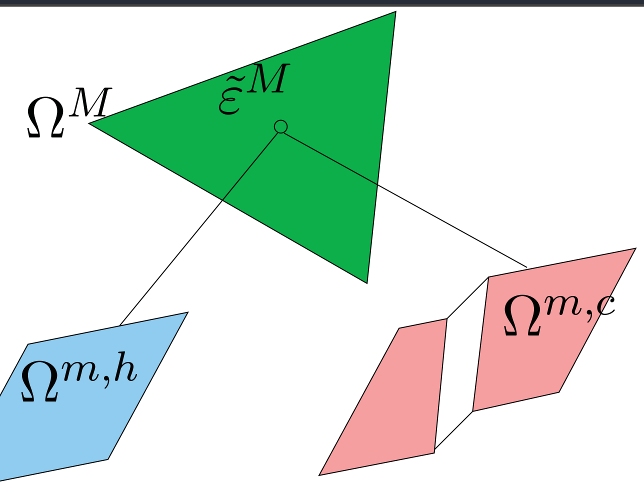
FE^2-X^1 - Energy scaling in 2D

Macroscopic element



$$\Pi(\Omega^M) \approx \frac{l^M}{l^{m,c}}\Pi(\Omega^{m,c}) + \frac{A^M - \frac{l^M}{l^{m,c}}A^{m,c}}{A^{m,h}}\Pi(\Omega^{m,h})$$

Boundary conditions

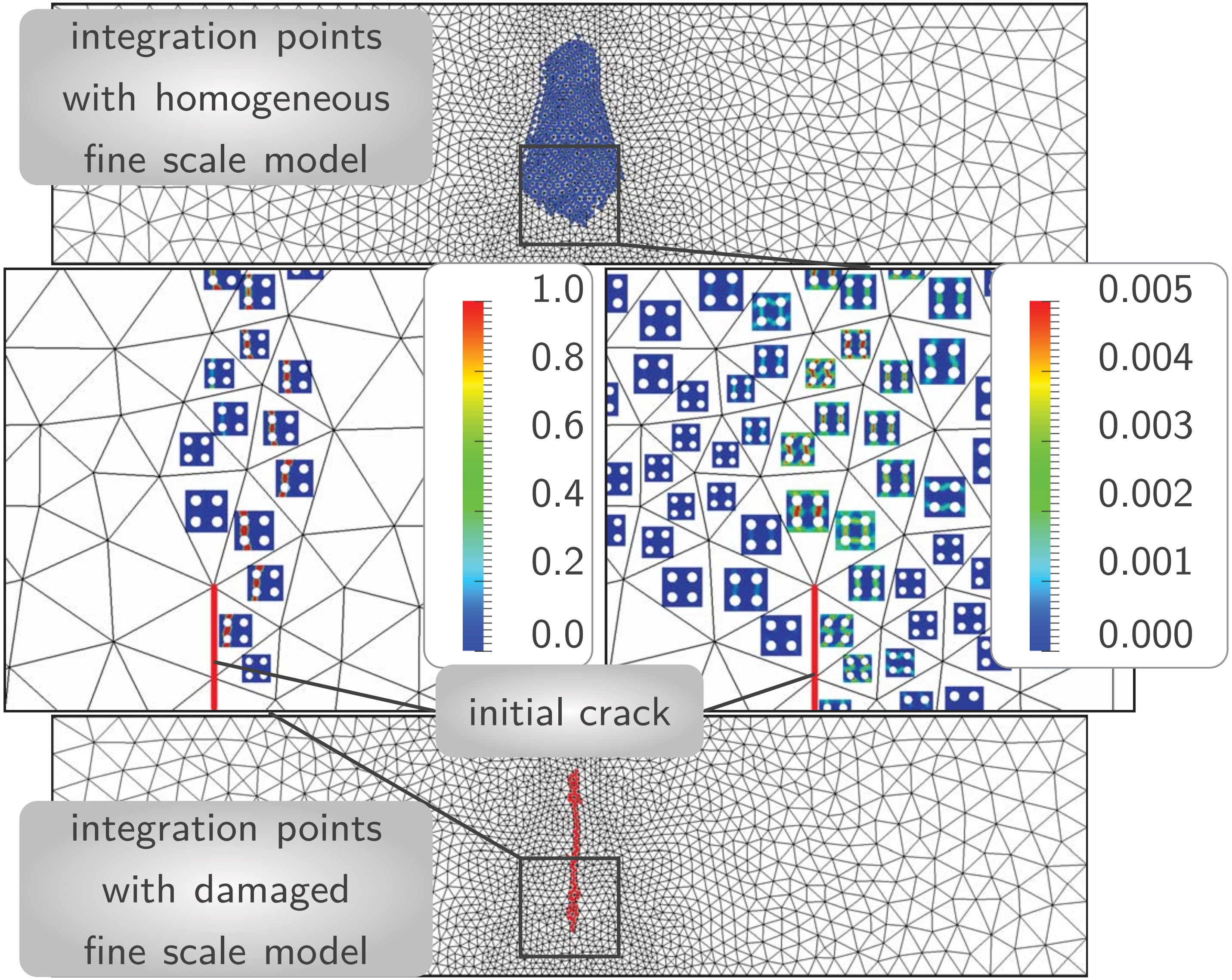


$$u = \bar{\varepsilon}X \qquad u = \bar{\varepsilon}X + \tilde{H}(X)[u]$$

- two fine scale models per macro IP
- distinction between crack opening and homogeneous strain
- constrained equation
  $$\tilde{\varepsilon}^M = \bar{\varepsilon} + \frac{1}{2l^M}\left([\boldsymbol{u}] \otimes \boldsymbol{n} + \boldsymbol{n} \otimes [\boldsymbol{u}]\right)$$

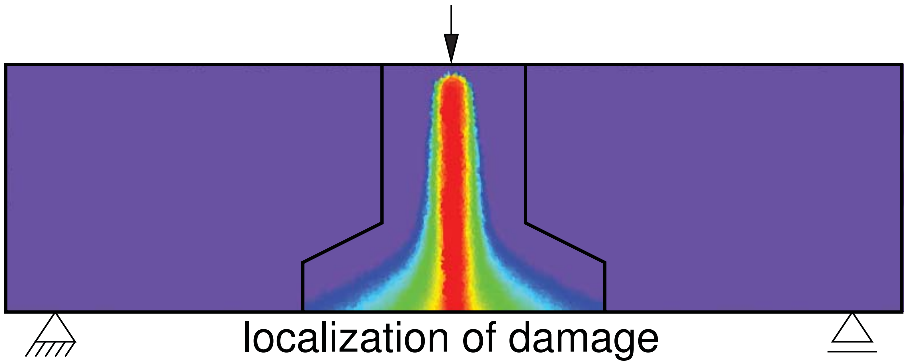
further information:[Unger, 2013]

Three-Point Bending Test

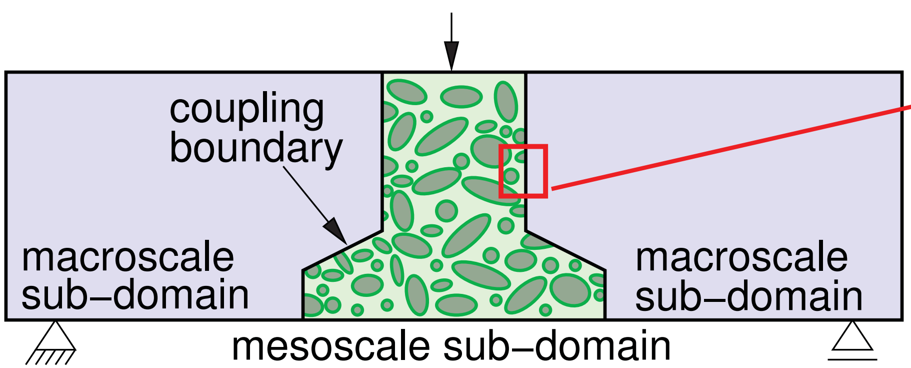


Heterogeneous multiscale approach

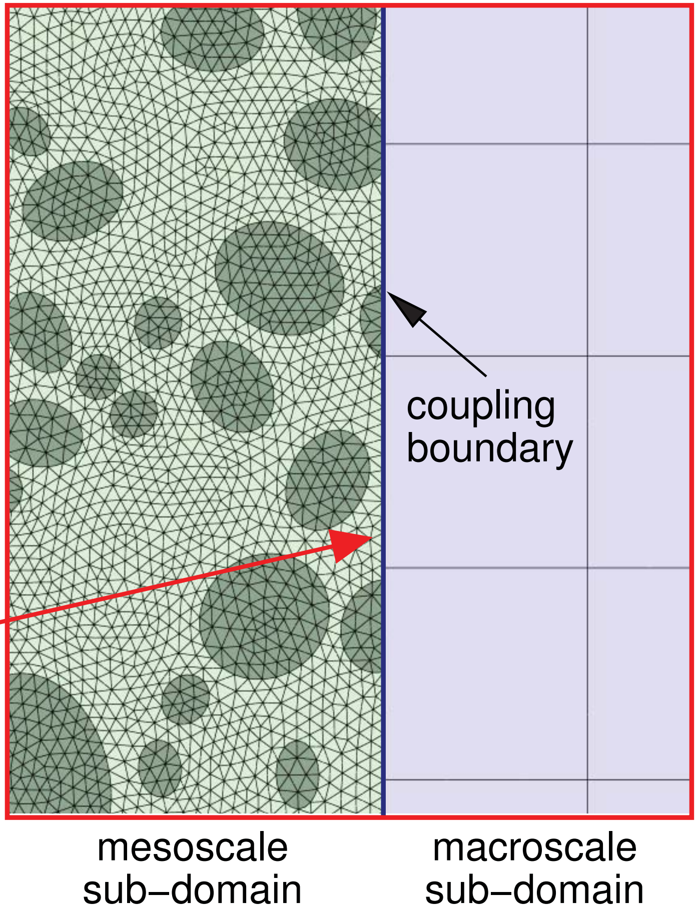
Macroscale model – damage



Heterogeneous multiscale model



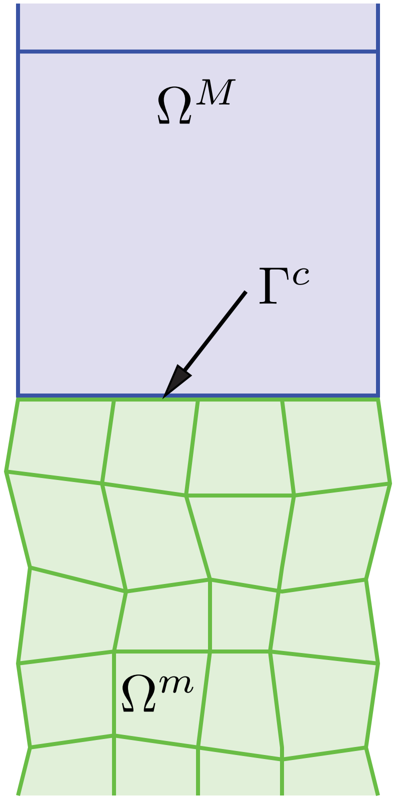
Coupling the scales



further information:[Unger et al., 2011]

Coupling of different domains

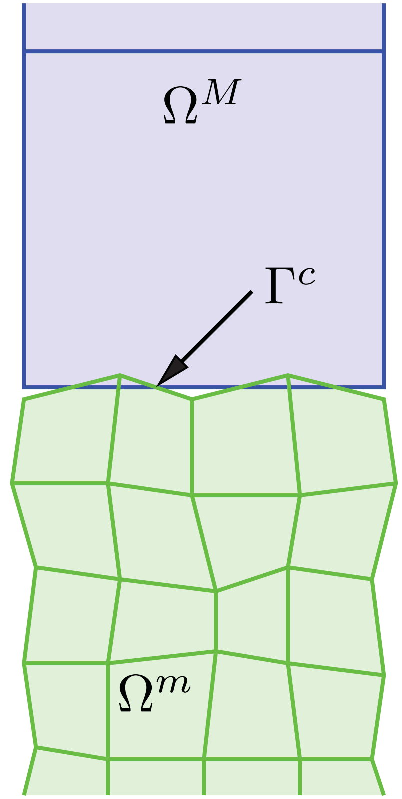
Strong coupling



constraint equations

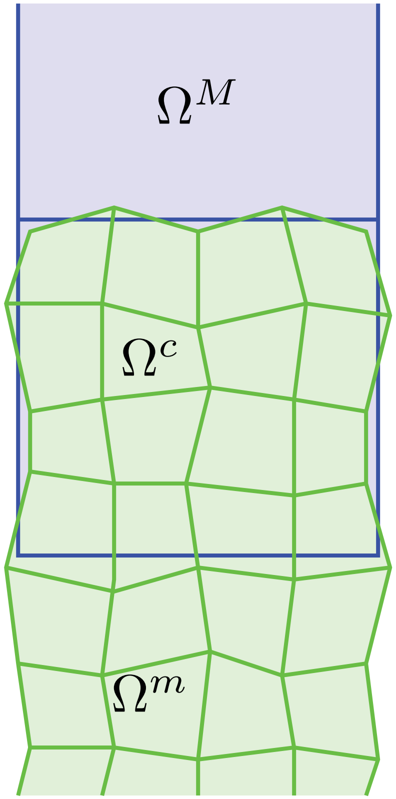
$$\boldsymbol{u}^{\boldsymbol{m}}(\boldsymbol{x}) = \boldsymbol{u}^{\boldsymbol{M}}(\boldsymbol{x}) \quad \forall \boldsymbol{x} \in \Gamma^c$$

Weak coupling



mortar method

$$\int_{\Gamma^c} [\boldsymbol{u}^{\boldsymbol{m}} - \boldsymbol{u}^{\boldsymbol{M}}] \, \mathrm{d}\Gamma^c = \boldsymbol{0}$$

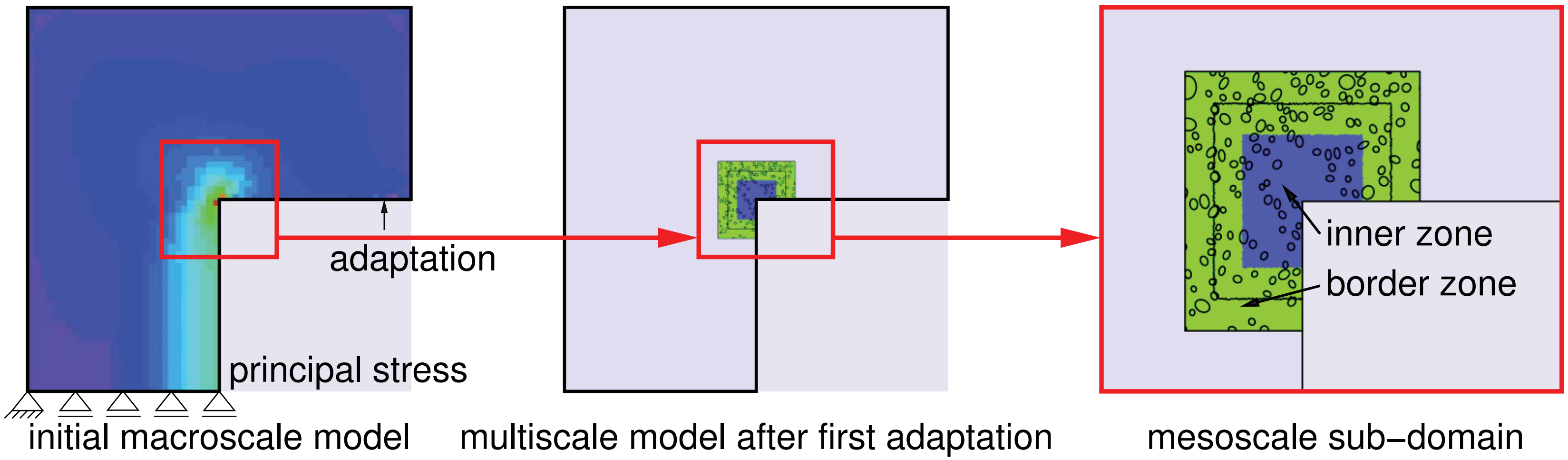


arlequin method

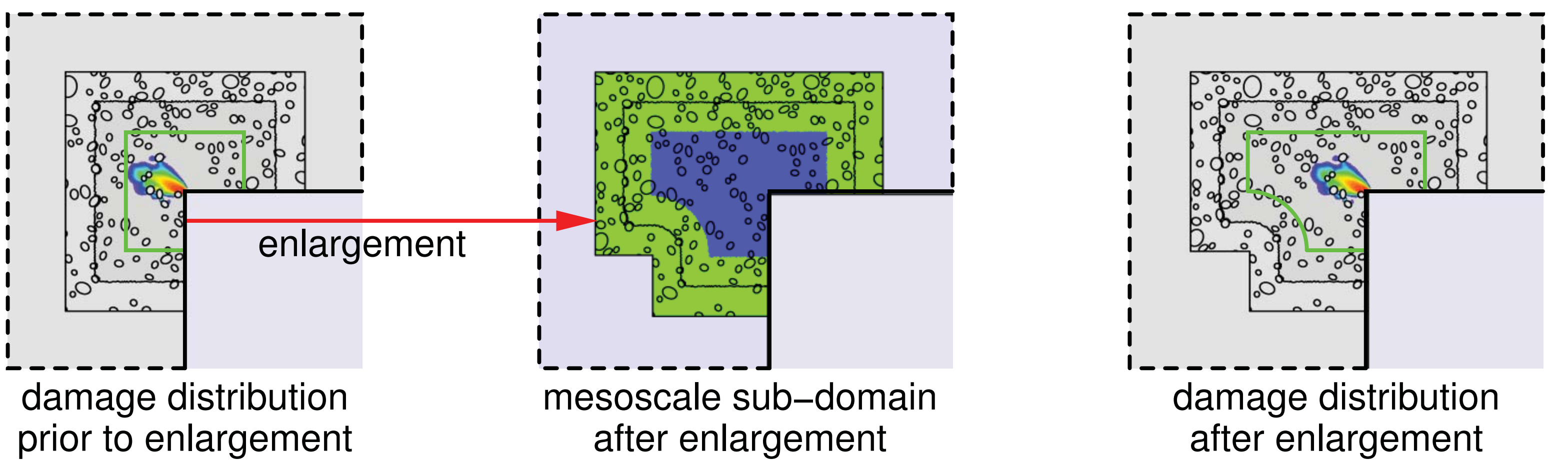
$$\int_{\Omega^c} [\boldsymbol{u}^{\boldsymbol{m}} - \boldsymbol{u}^{\boldsymbol{M}}] \, \mathrm{d}\Omega^c = \boldsymbol{0}$$

Adaptation

Generation of a new mesoscale sub-domain

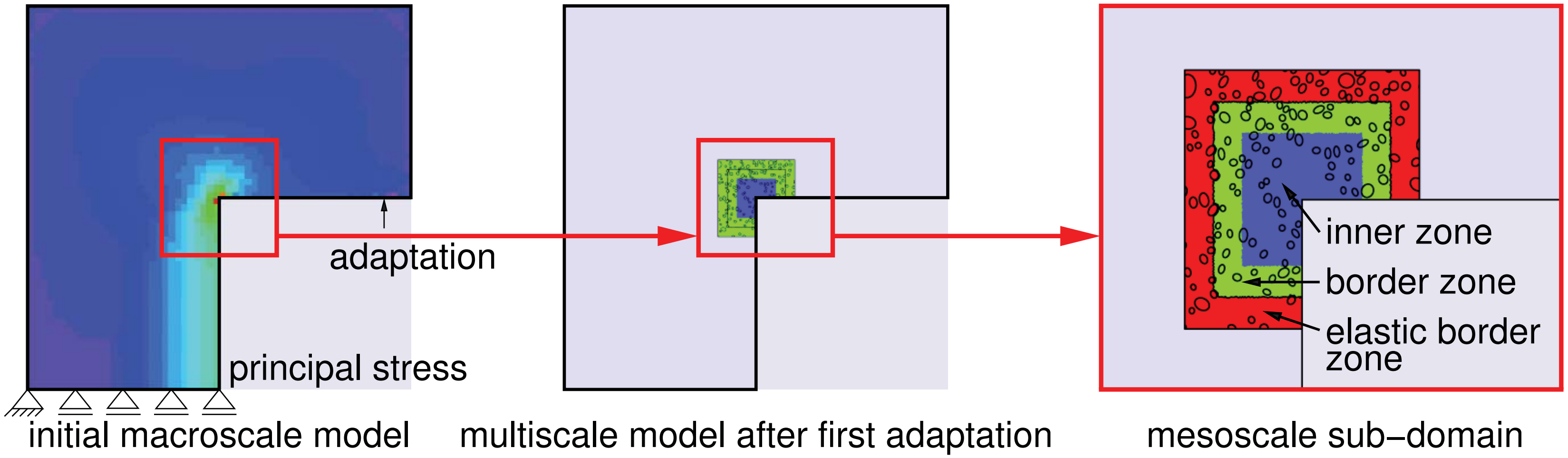


Enlargement of an existing mesoscale sub-domain

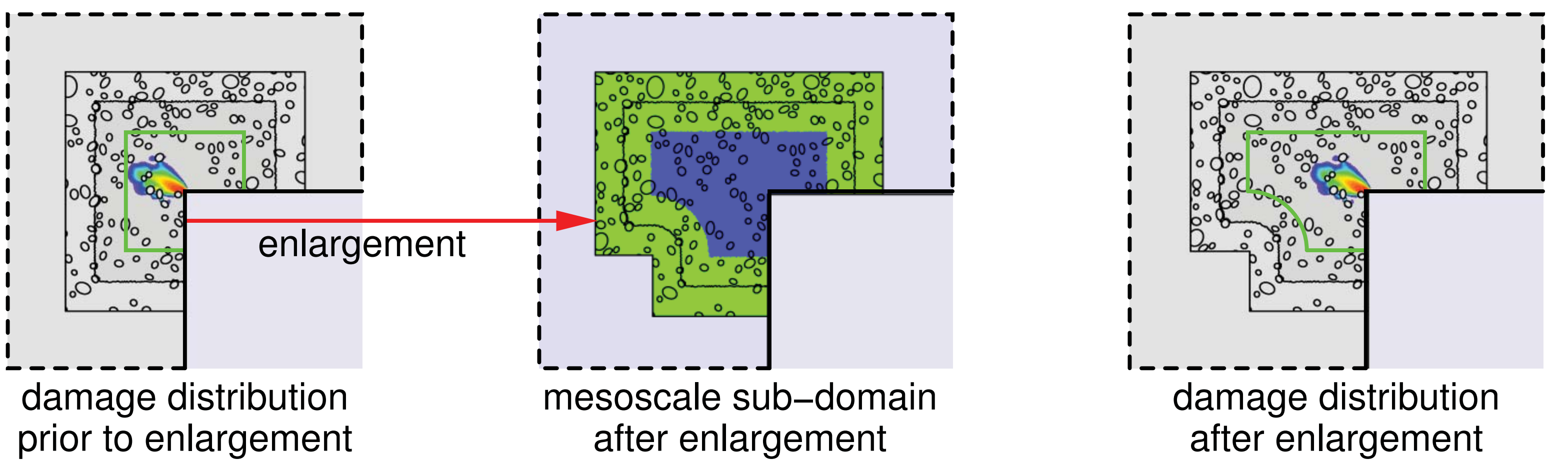


Adaptation

Generation of a new mesoscale sub-domain

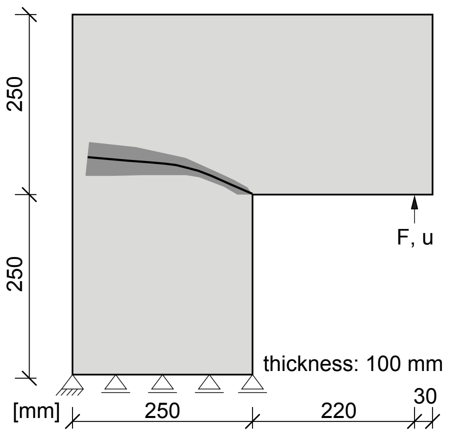


Enlargement of an existing mesoscale sub-domain



L-shaped panel (Experiments by Winkler)

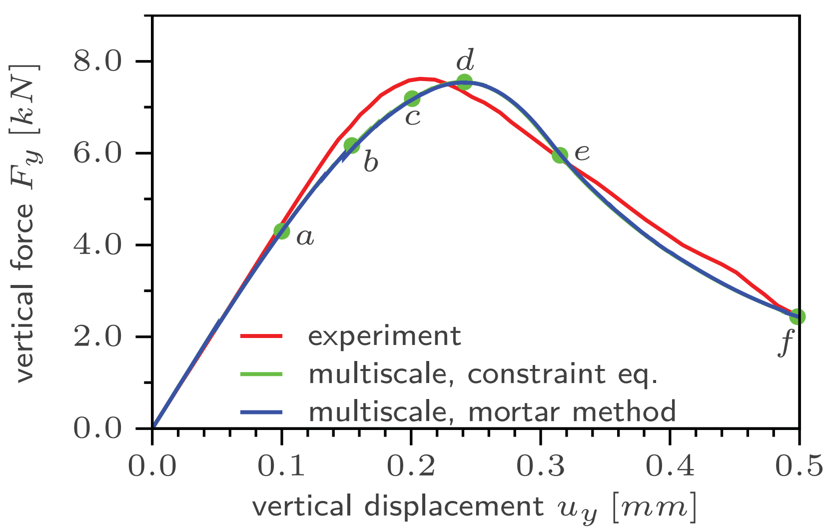
Specimen geometry



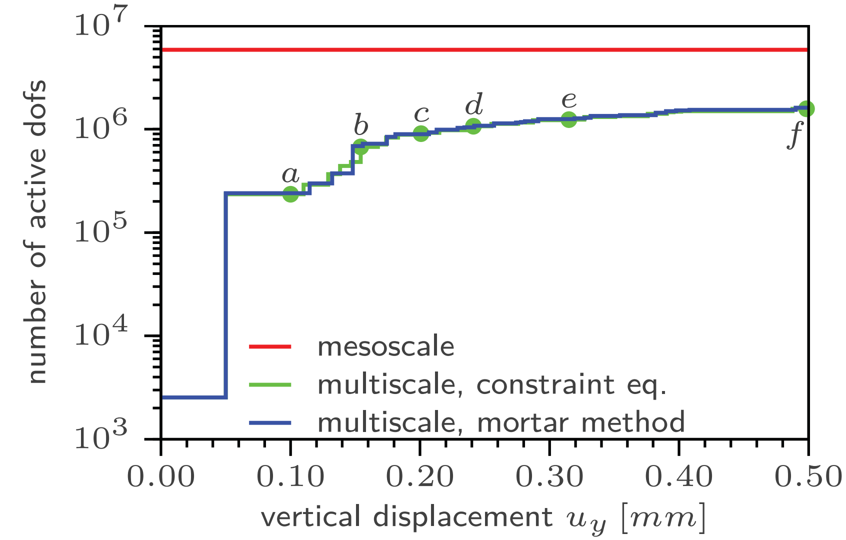
material parameters $[N, mm]$

	Concrete	Mortar	Aggregates	ITZ
E	20 000	18 500	37 000	500 000
ν	0.18	0.18	0.18	–
f_t	–	2.60	–	1.30
G_f	–	0.14	–	0.07
R	–	0.75	–	–
α	–	–	–	1.0

Load-displacement curve



Number of active dofs



L-shaped panel – Damage

Conclusions

- mesoscale models capture complex macroscopic phenomena
- multiscale models required to simulate real problems
- concurrent or hierarchical methods suited to model localization phenomena

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TU1404 COST ACTION

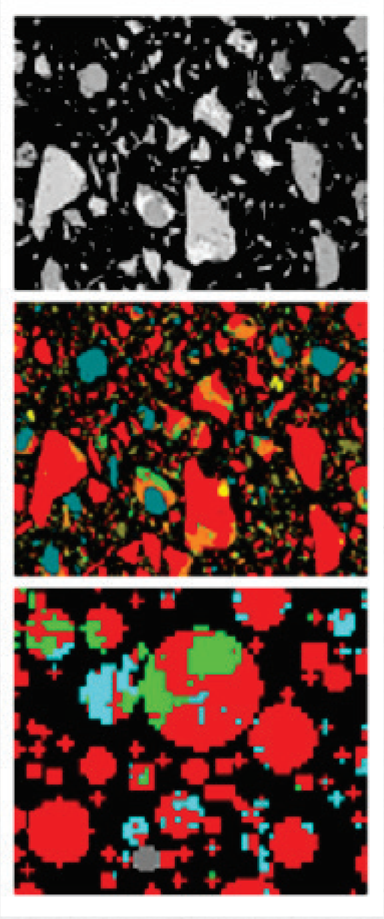
Micro-scale modelling of cement hydration and properties evolution

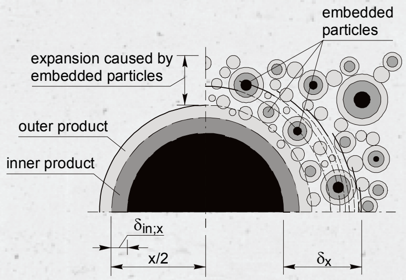
Ye Guang – Delft University of Technology, the Netherlands

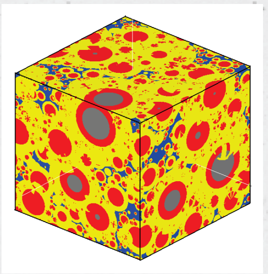
Microlab

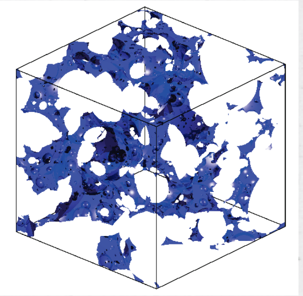
TU Delft

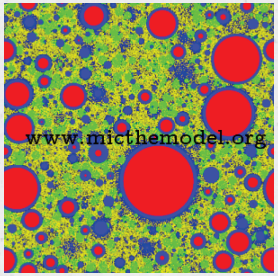
Current microstructural models











CEMHYD3D / VCCTL

Bentz, 2005/Bullard, 2014

HYMOSTRUC3D

van Breugel, 1991, Koenders, 1997, Ye 2003

μic

Bishnoi/Scrivener, 2008

Cement hydration and Stoichiometry

Hydration of Portland cement *(Taylor 1997)*

$$2C_3S + 5.6H_2O \rightarrow C_3S_2H_3 + 2.6CH, \quad \Delta H = 120 \text{ cal/g}$$

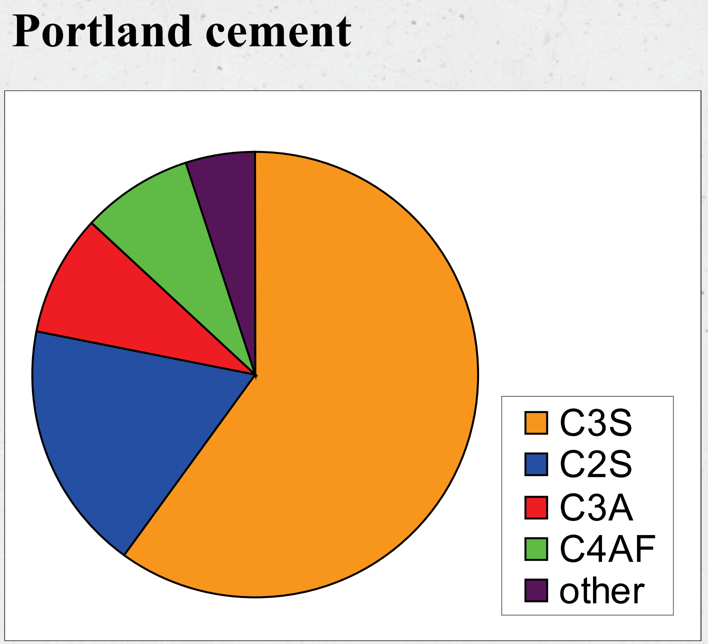
$$2C_2S + 3.6H_2O \rightarrow C_3S_2H_3 + 0.6CH, \quad \Delta H = 62 \text{ cal/g}$$

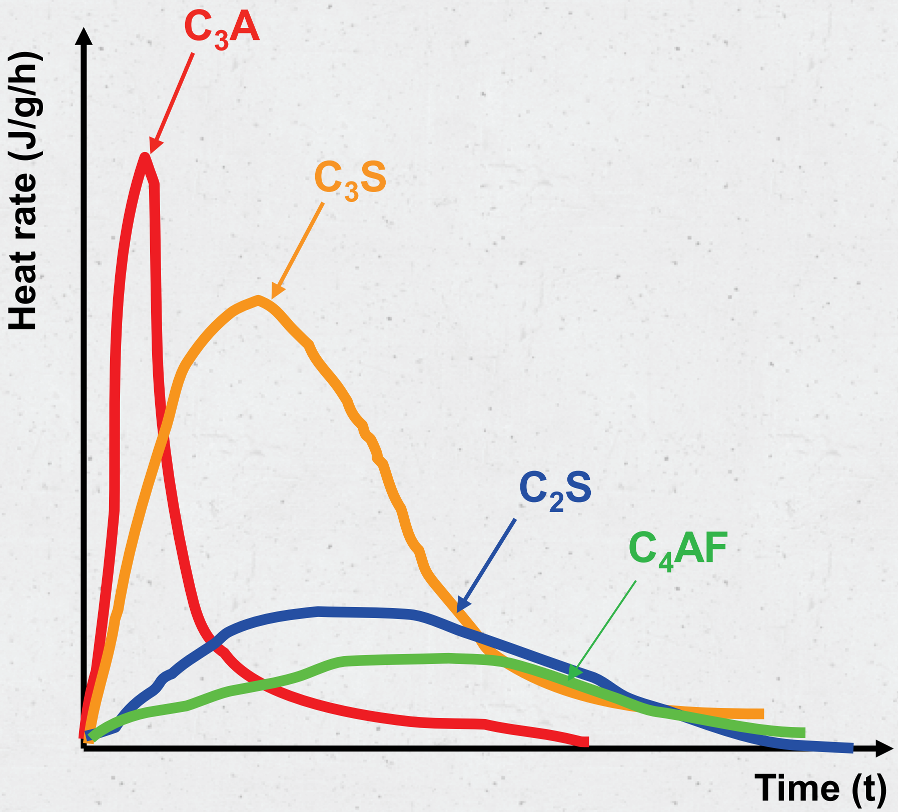
$$C_3A + 3C\underline{S}H_2 + 26H_2O \rightarrow C_6A\underline{S}_3H_{32}, \quad \Delta H = 207 \text{ cal/g}$$

$$C_4AF + 3C\underline{S}H_2 + 30H_2O \rightarrow C_6(A,F)\underline{S}_3H_{32} + (A,F)H_3 + CH$$

What phases present?

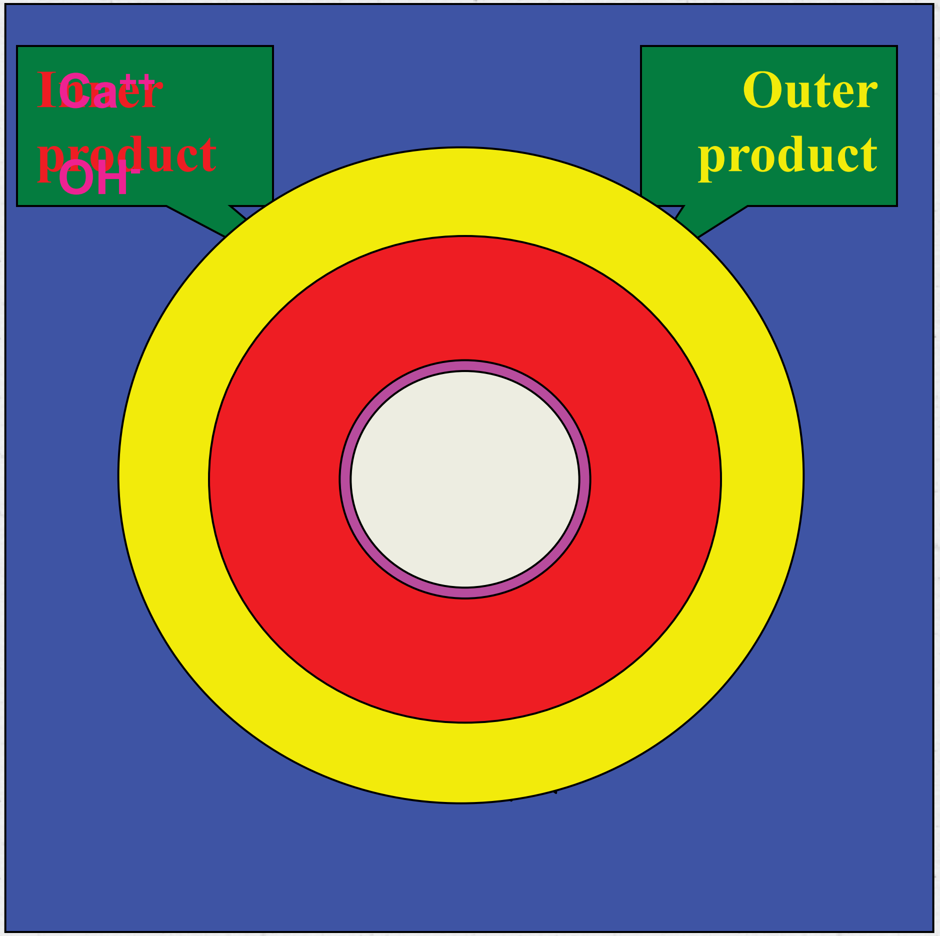
Kinetics of Cement hydration

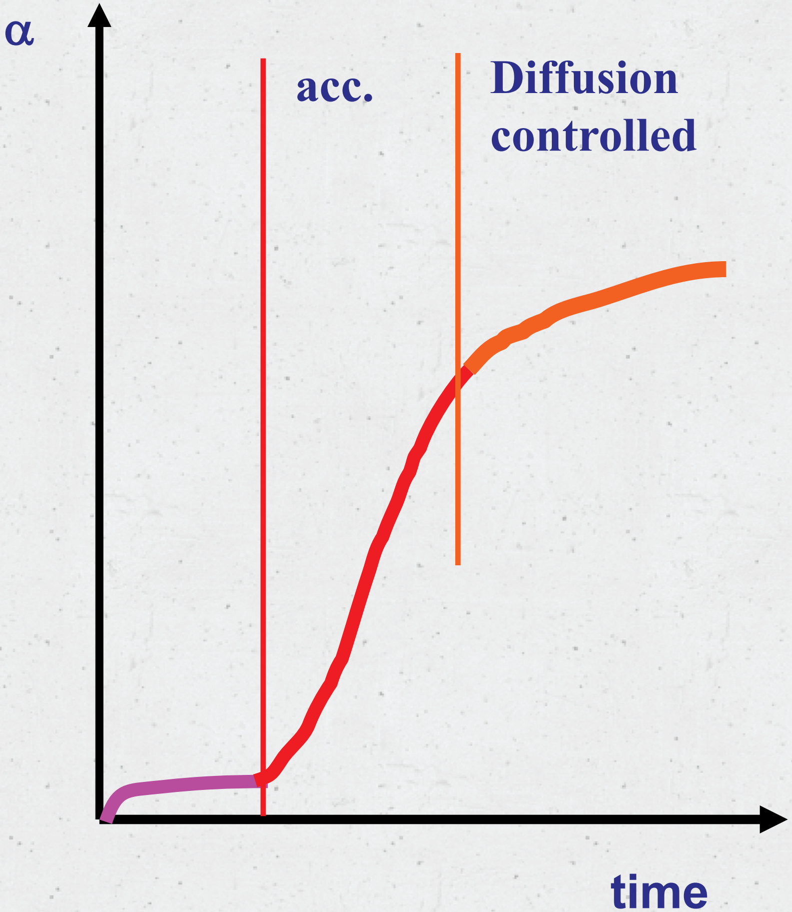




Degree of hydration of poly-mineral and poly-size systems
Degree of hydration is a weighed average

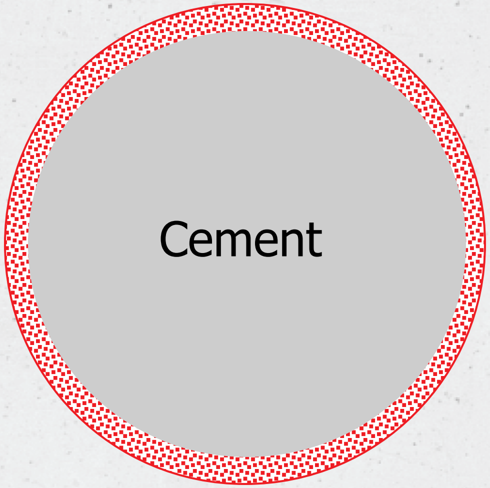
Cement hydration - single particle

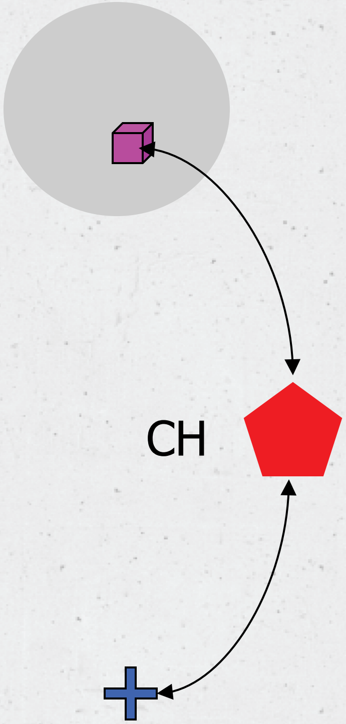


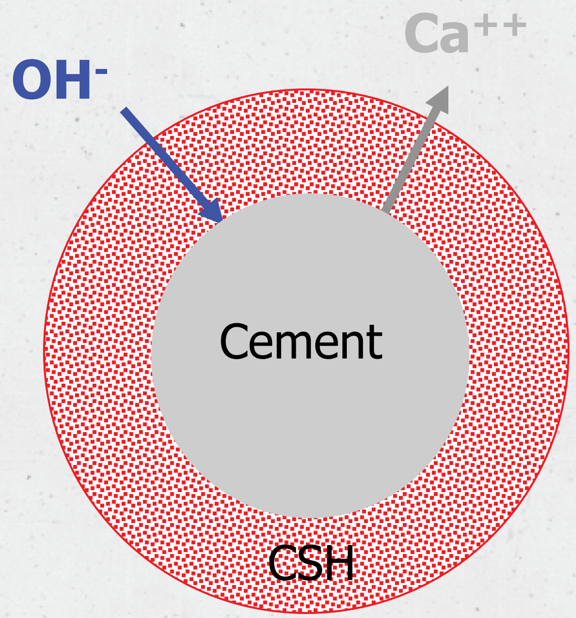


Stages in hydration process

Cement hydration - single particle







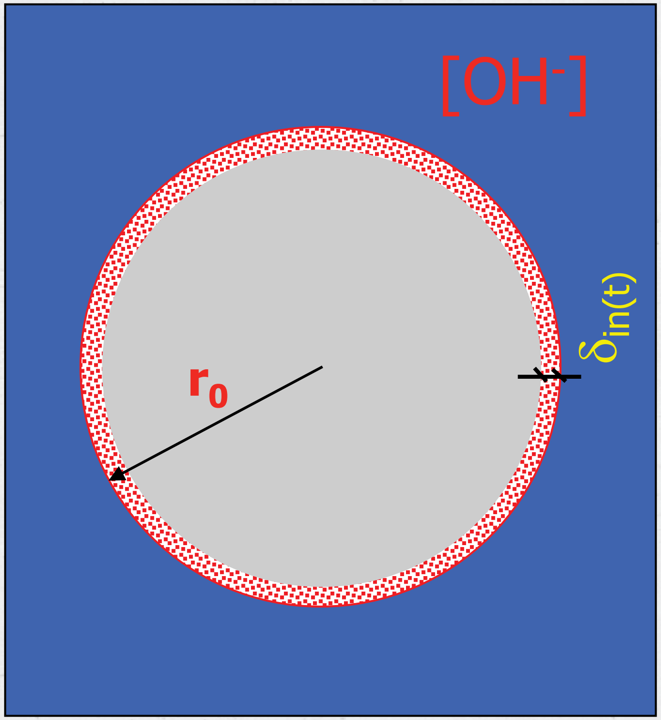
Phase-Boundary reaction

Nucleation

Diffusion controlled reaction

Particle kinetics

Phase-Boundary reaction



For **a spherical particle** with radius r_0=x/2 of the reactant and penetration depth $\delta_{in}(t)$, the degree of hydration is:

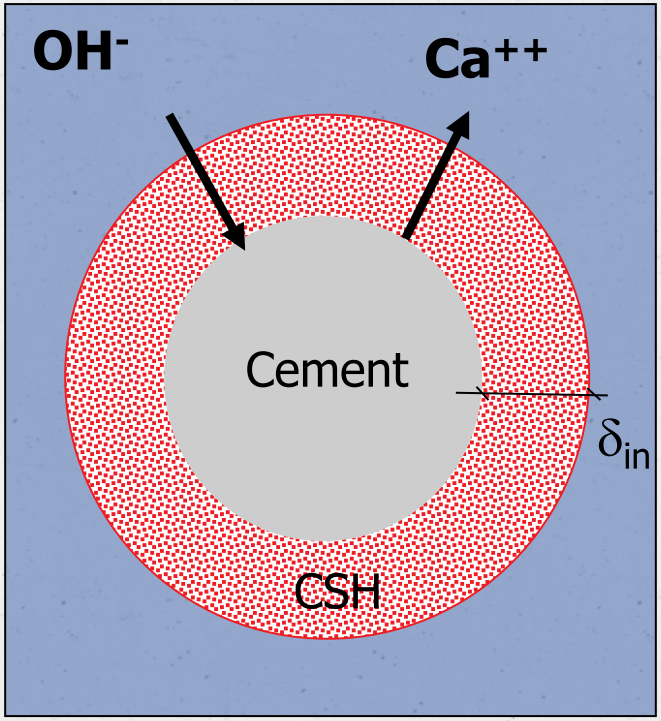
$$\alpha_{x;\delta_{in}} = 1 - \left[1 - \frac{\delta_{in;x}(t)}{r_0}\right]^3$$

the penetration depth $\delta_{in}(t)$ is

$$\delta_{in;x}(t) = k \times t = r_0 \times \left[1 - (1 - a_{x;\delta_{in;x}})^{\frac{1}{3}}\right]$$

Particle kinetics

Diffusion controlled reaction



- Jander

$$[1-(1-a_x)^{\frac{1}{3}}]^N = \frac{2.k.t}{r_0^2}$$

- Ginstling and Brownshtein

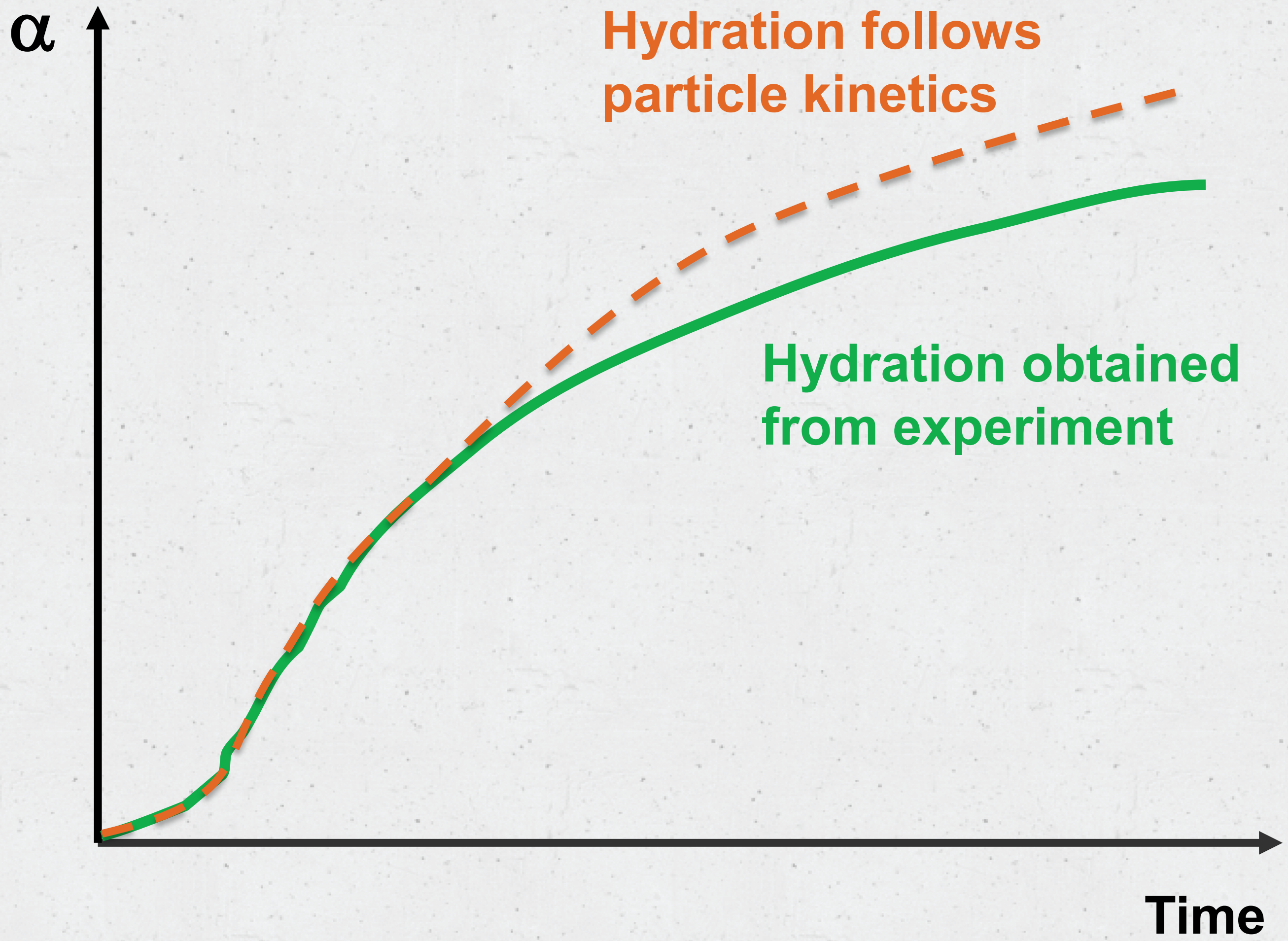
$$[1-\frac{2a_x}{3}]-(1-a_x)^{\frac{2}{3}} = k.t$$

- Carter

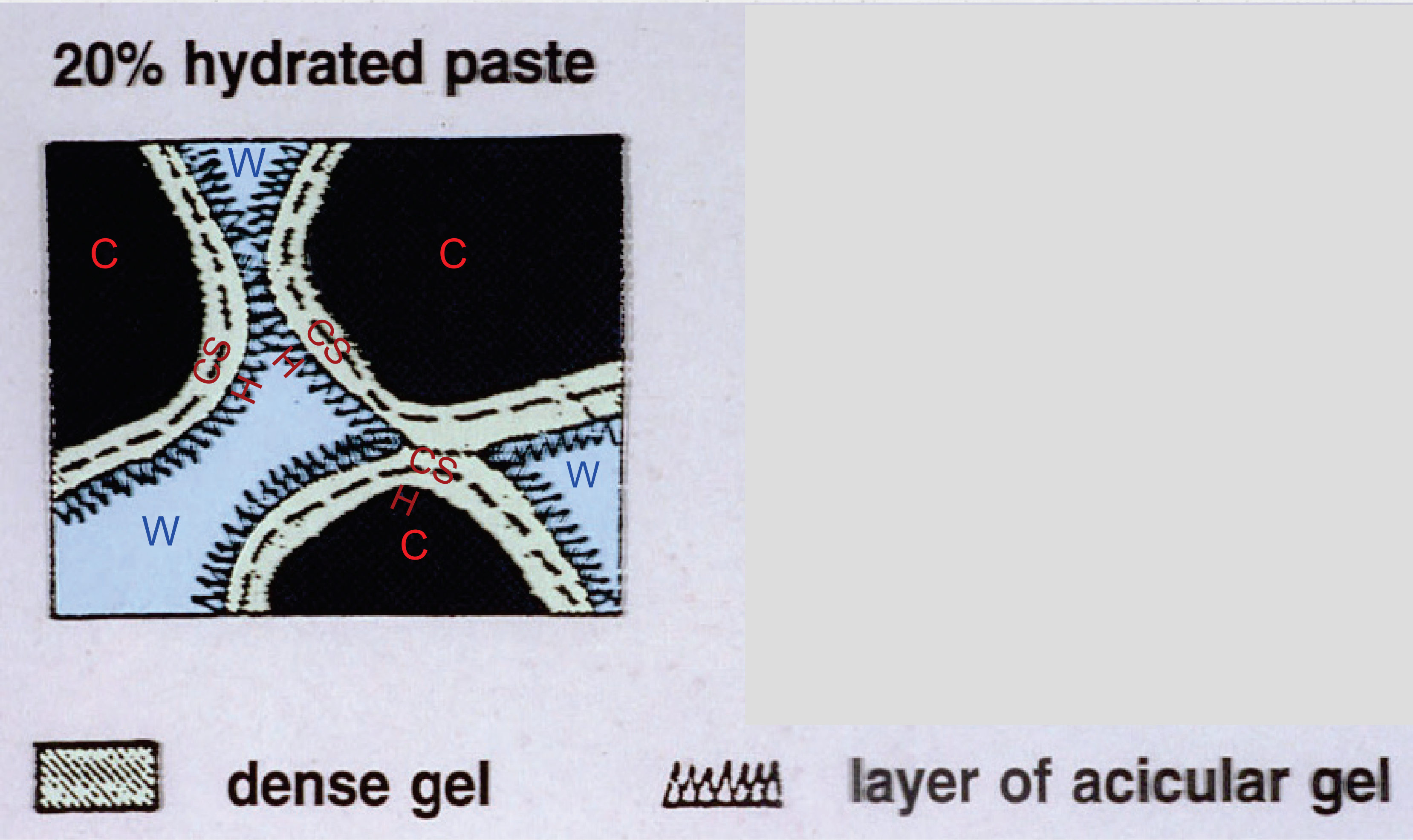
$$[1+(v-1)\times a_x]^{\frac{2}{3}} + (v-1)\times(1-a_x)^{\frac{2}{3}} - v = k.t$$

ν, the ratio of the v. of the reaction products relative to that of the dissolved part of the reactant

Particle kinetics



Particle interaction



Cranju & Maso (1984)

Integrated kinetics – HYMOSTRUC

Chemical reaction affected by physical contact between hydrating cement particles

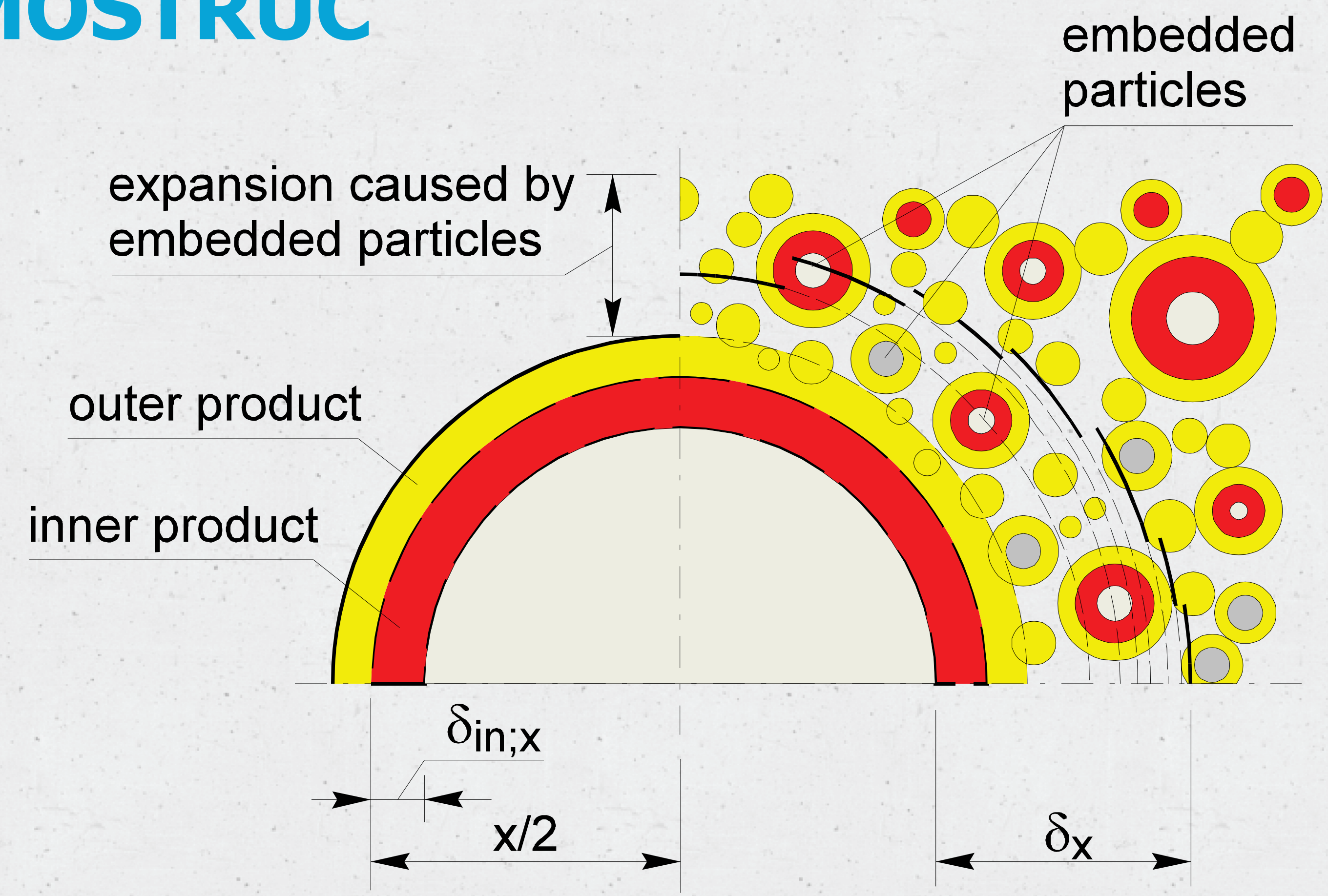
↓

Interaction between hydration kinetics and microstructural development

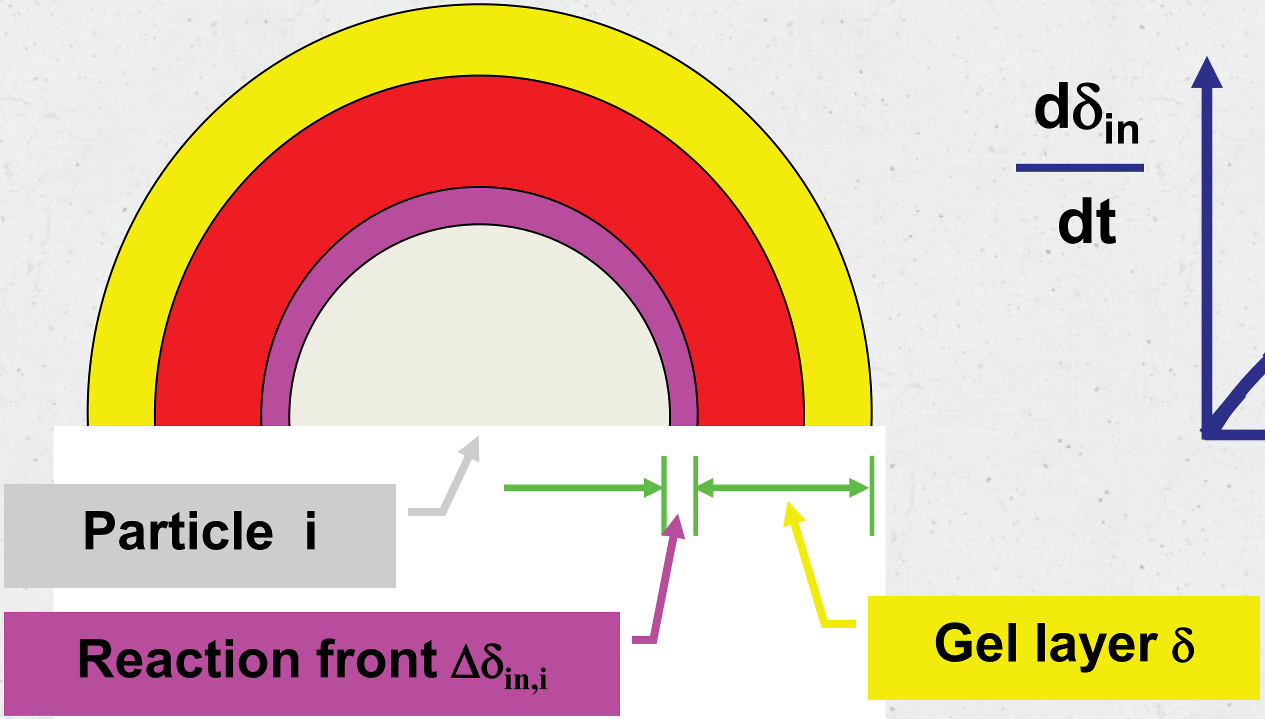
↓

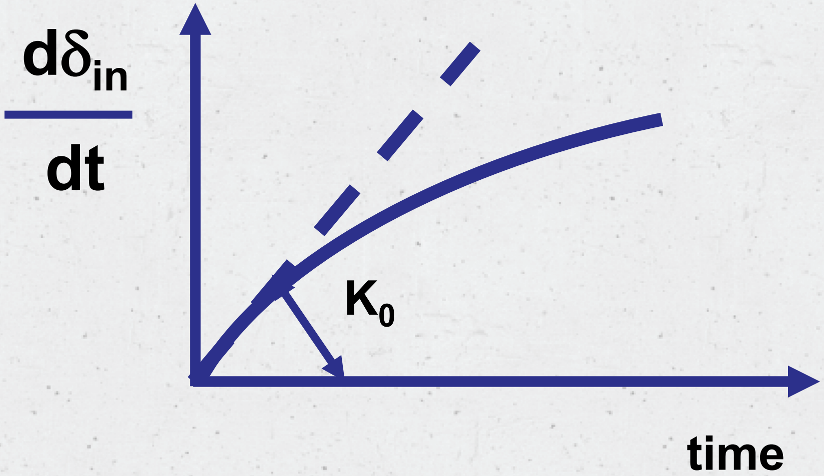
Integrated kinetics

HYMOSTRUC



Particle interaction due to outward growth, van Breugel 1991





Basic rate formula:

$$\frac{d\delta_{in,i}}{dt} = K_0 * \Omega_1 * \Omega_2 * \Omega_3 * F_1 * F_2 * \left\{ \frac{\delta(\alpha_i)}{\delta_{tr}} \right\}^{\lambda}$$

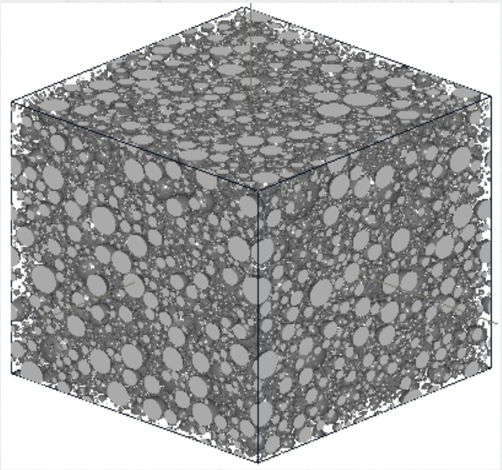
Rate of penetration of reaction front in particle i

Input for simulation

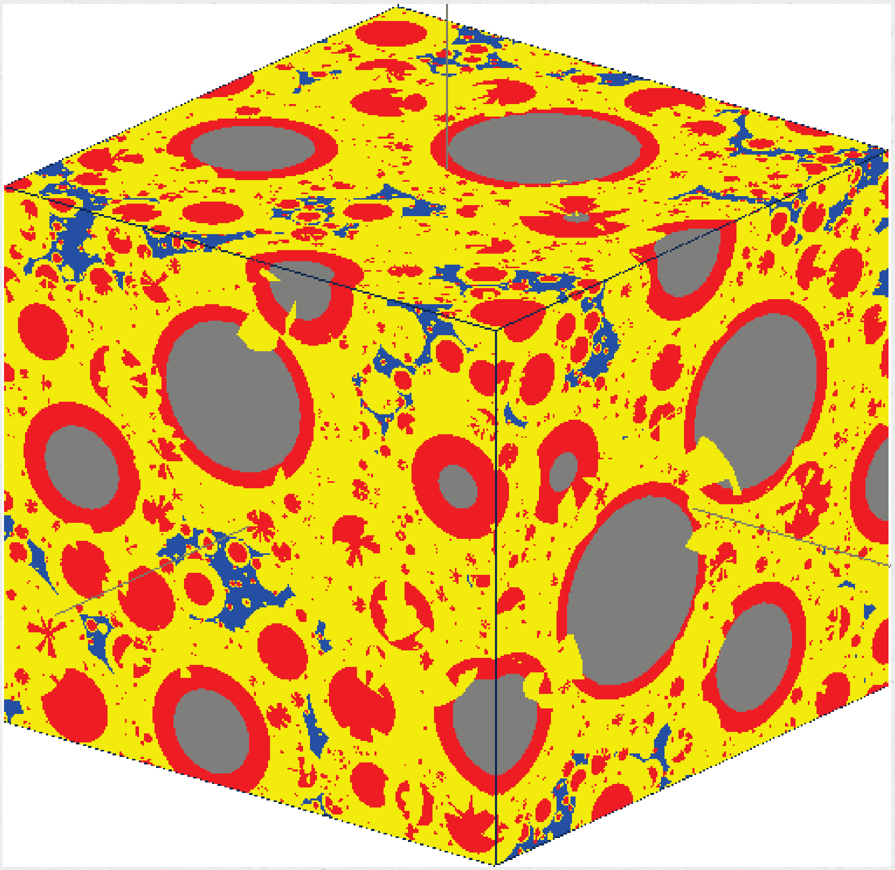
- Particle size distribution
- w/c
- Simulation body (shape and size)

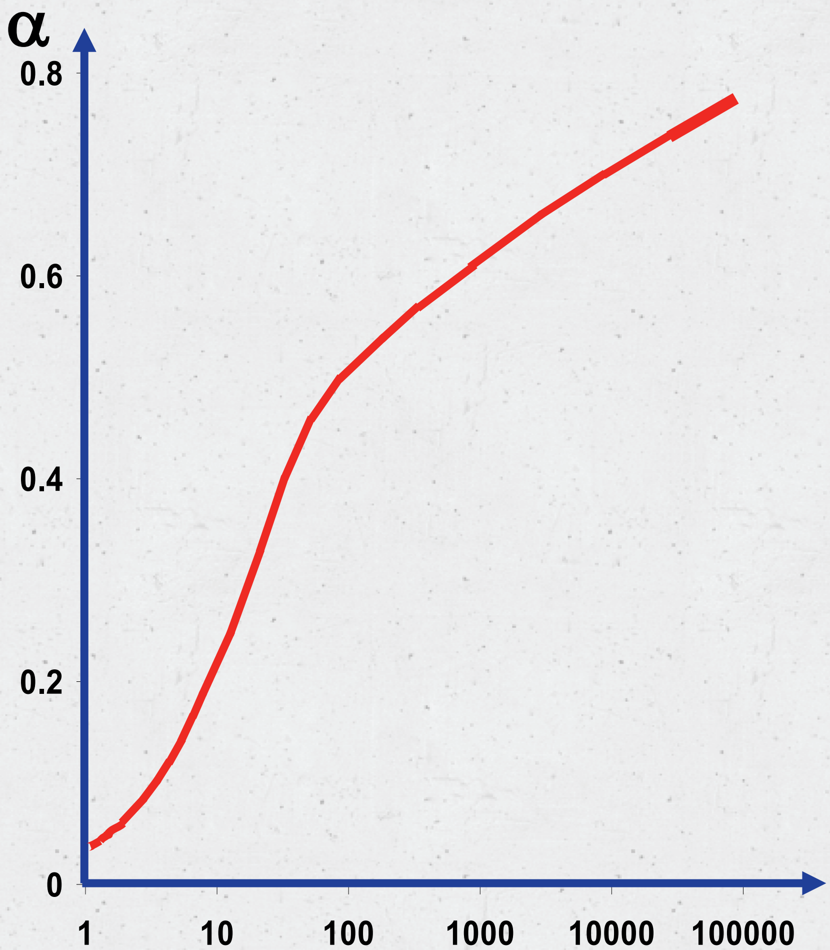
Number of cement particles

Particles random distribution



3D Microstructure simulation

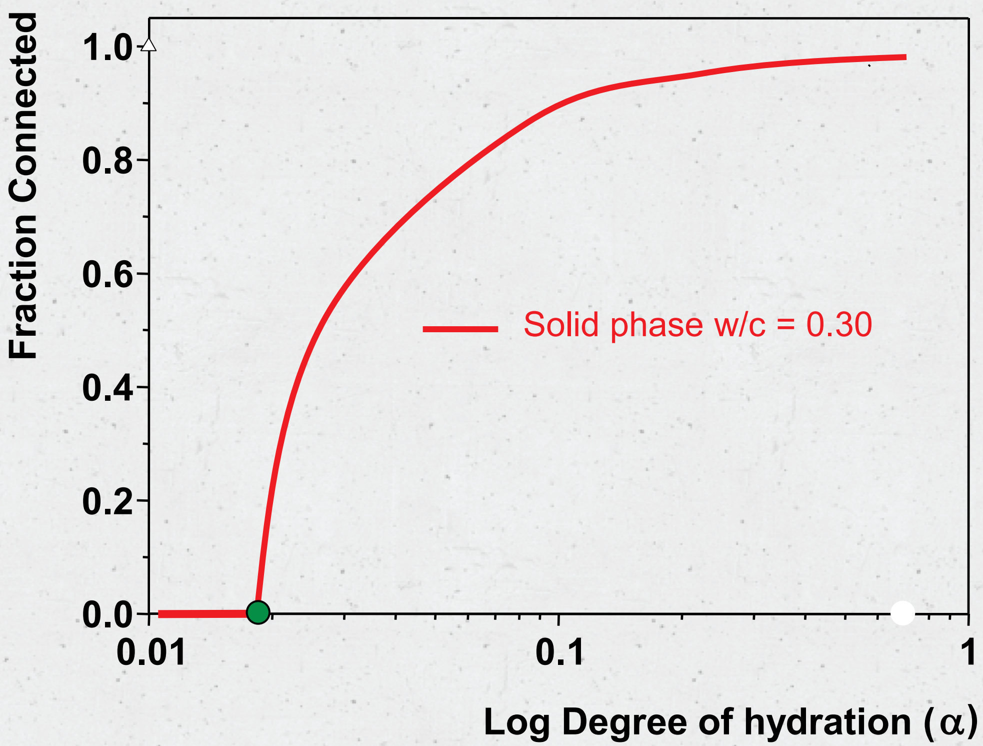




3D simulated cement paste (w/c=0.35)

Connectivity of solid phase

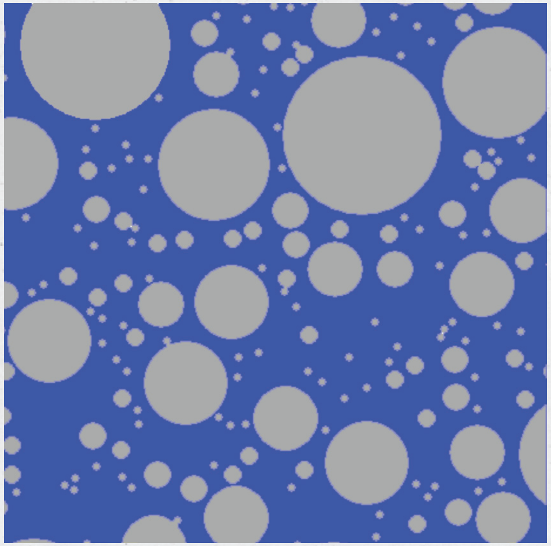
Percolation of solid phase and the setting of cement paste

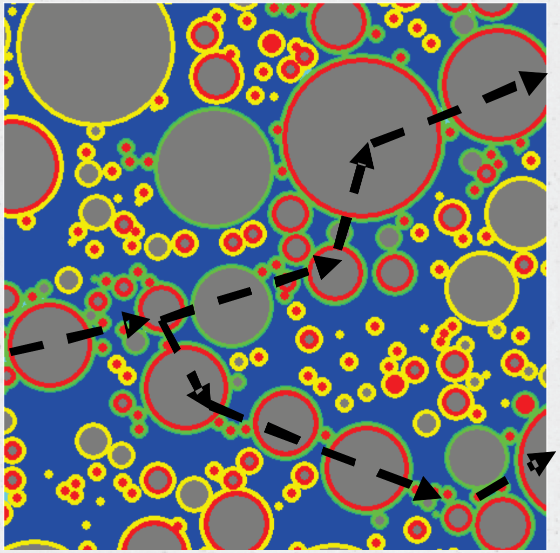


G. Ye, K. van Breugel, and A.L.A. Fraaij, “Experimental study and numerical simulation on the formation of microstructure in cementitious materials at early age”. Cement and Concrete Research, vol 33, No.2, 2003, pp 233-239.

Connectivity of solid phase

Percolation of solid phase and the setting of cement paste





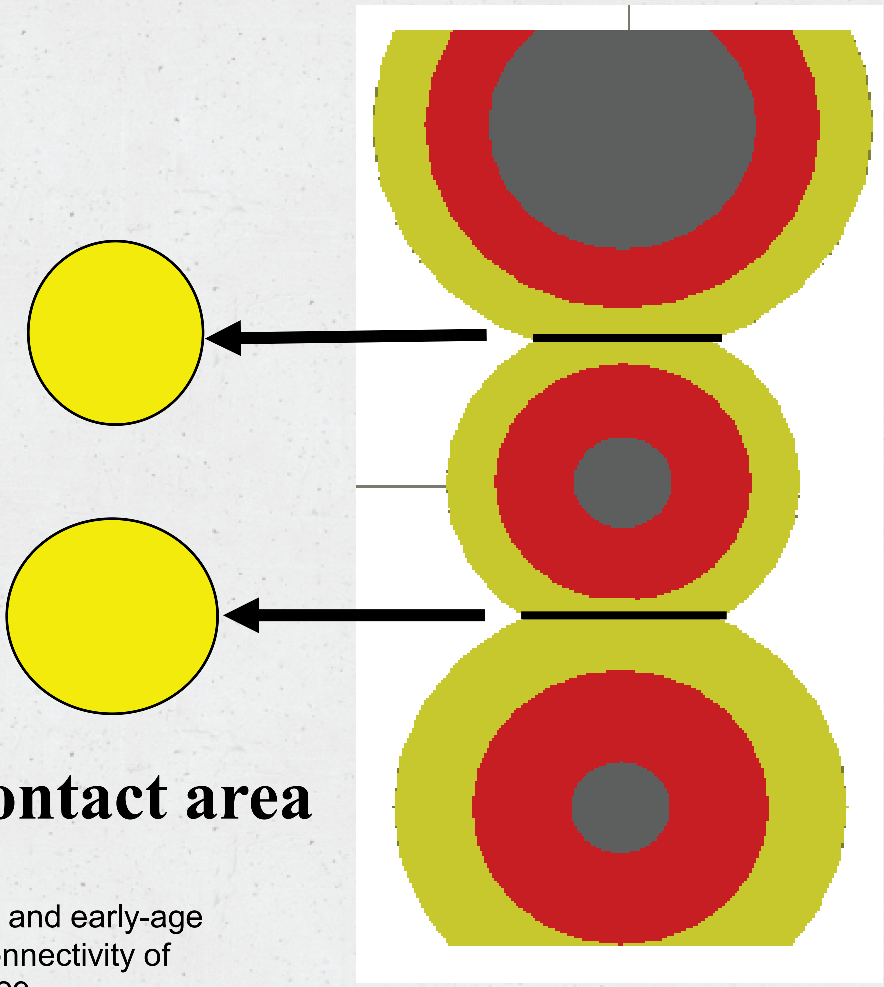
(a) Initial status: solid particles suspend in water, α = 0%

(b) Solid phase is percolated at α = 2%

G. Ye, K. van Breugel, and A.L.A. Fraaij, "Experimental study and numerical simulation on the formation of microstructure in cementitious materials at early age". Cement and Concrete Research, vol 33, No.2, 2003, pp 233-239.

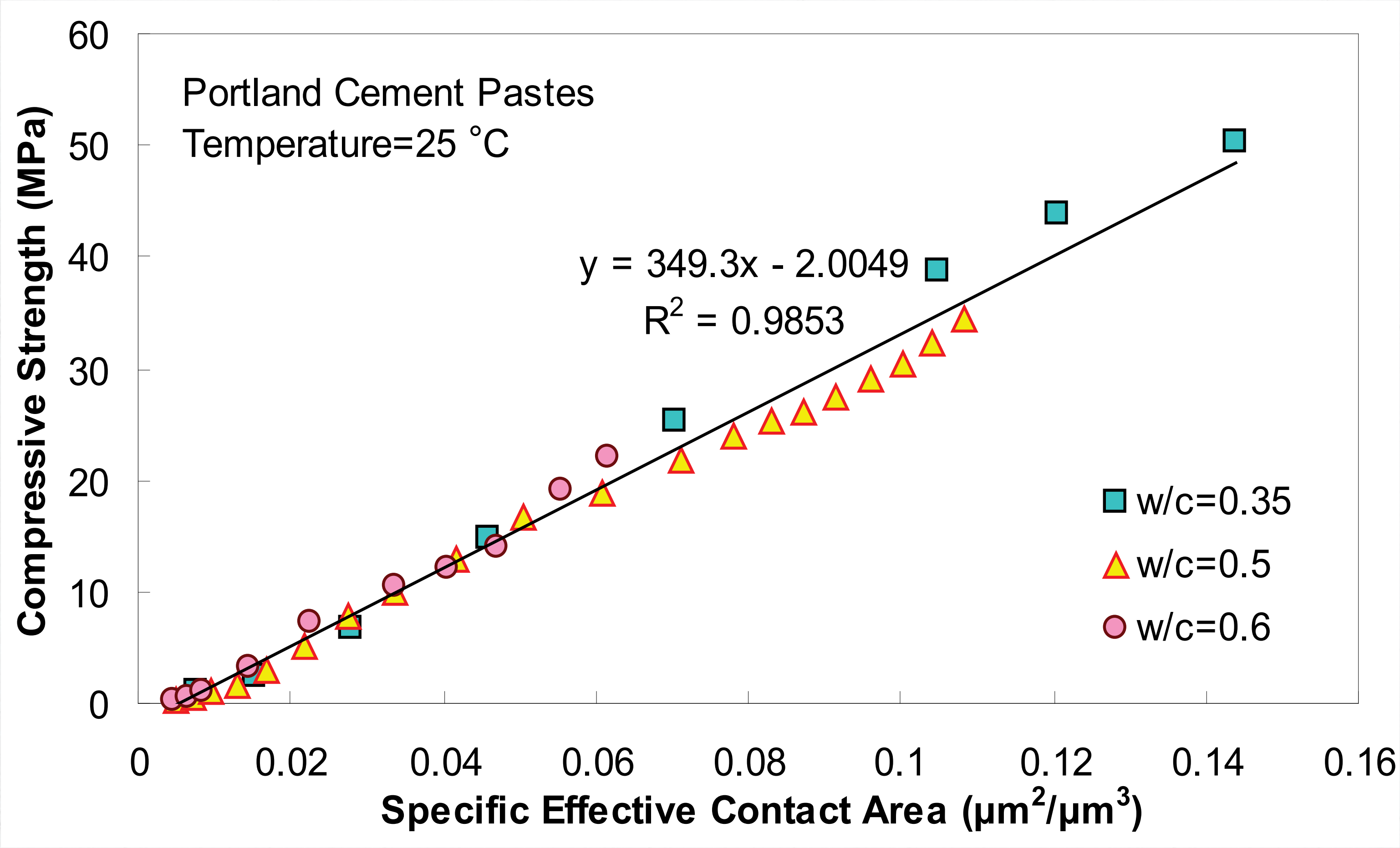
Connectivity of solid phase

Contact area concept



Sun, Z, Ye, G , & Shah, SP (2005). Microstructure and early-age properties of Portland cement paste - effects of connectivity of solid phases. ACI materials journal, 102(2), 122-129

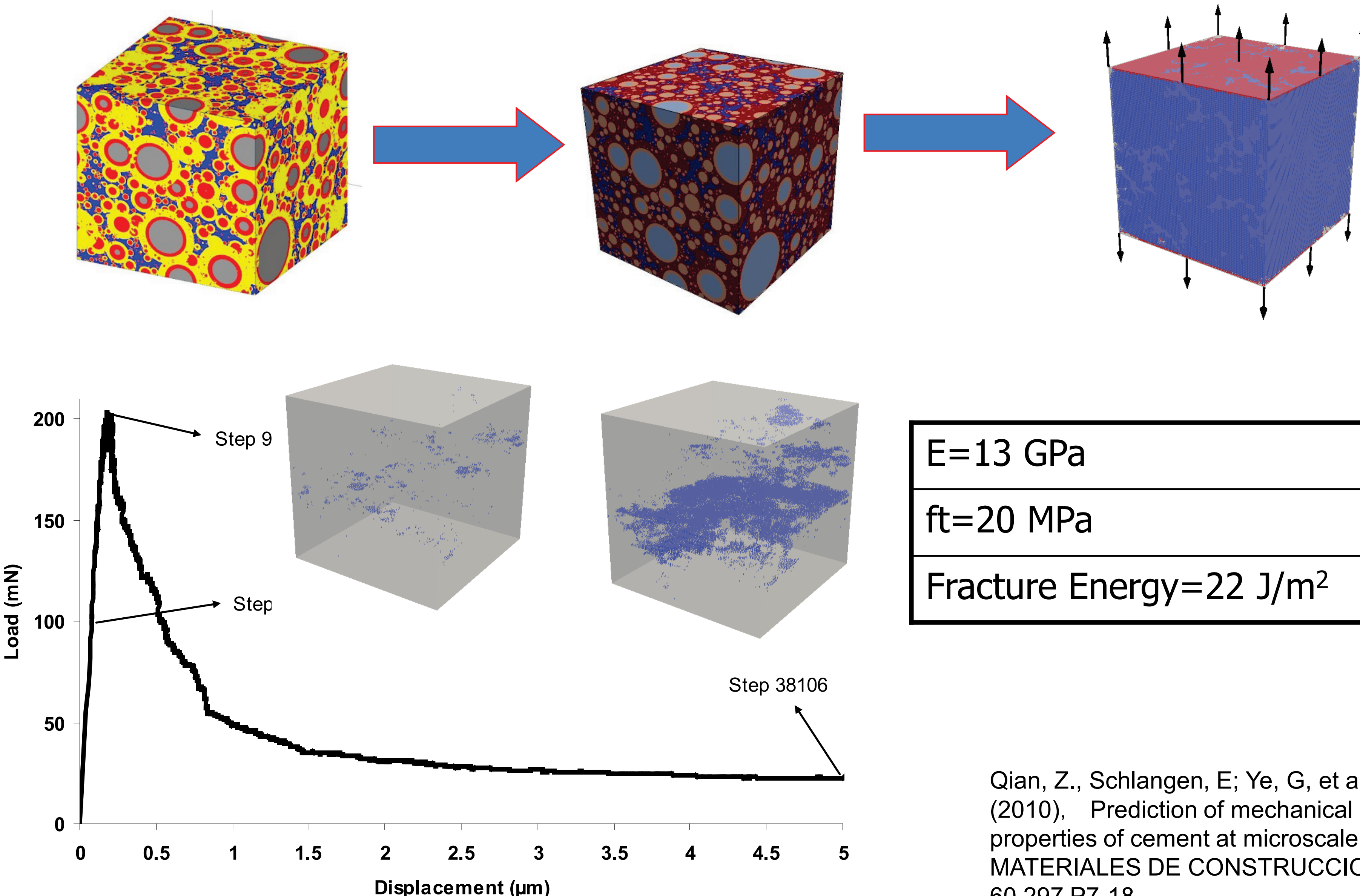
Connectivity of solid phase



Sun, Z, Ye, G , & Shah, SP (2005). Microstructure and early-age properties of Portland cement paste - effects of connectivity of solid phases. ACI materials journal, 102(2), 122-129

Compressive strength vs. Contact area

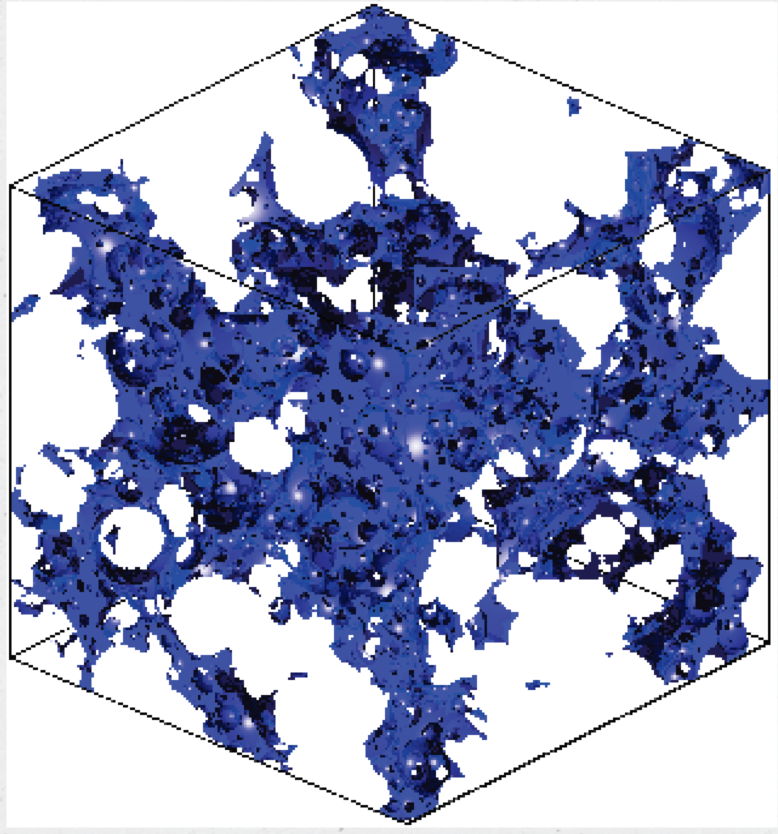
Mechanical Performance Evaluation

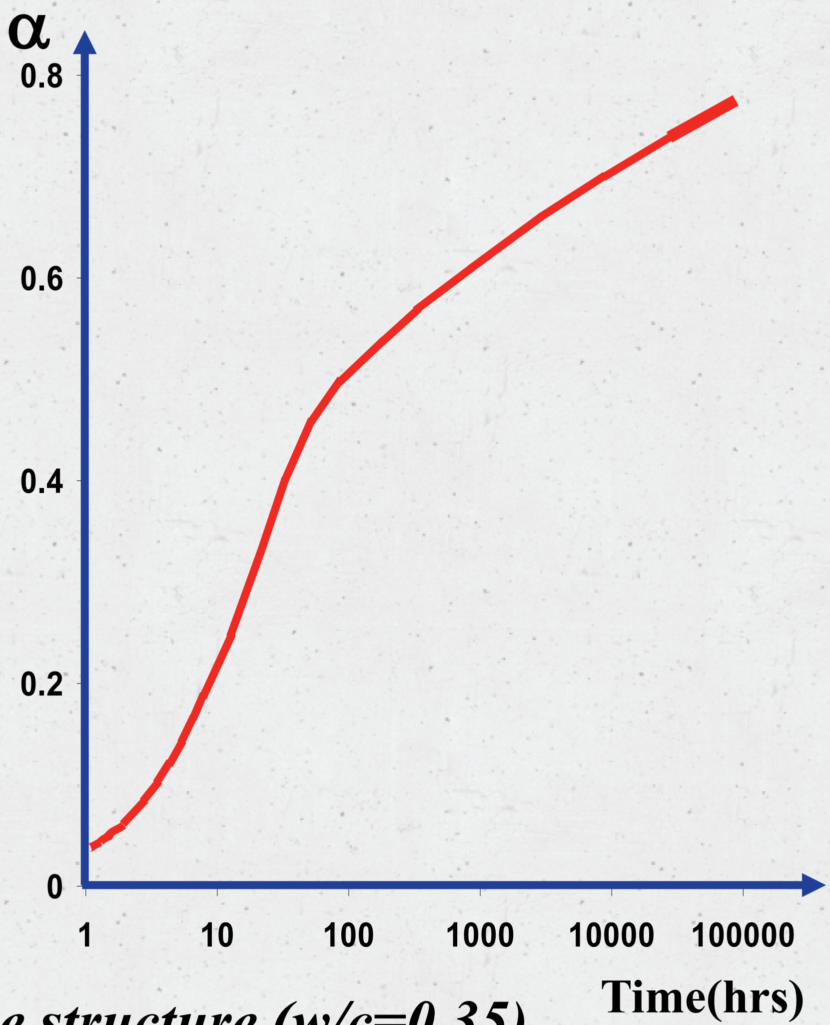


E=13 GPa
ft=20 MPa
Fracture Energy=22 J/m^2

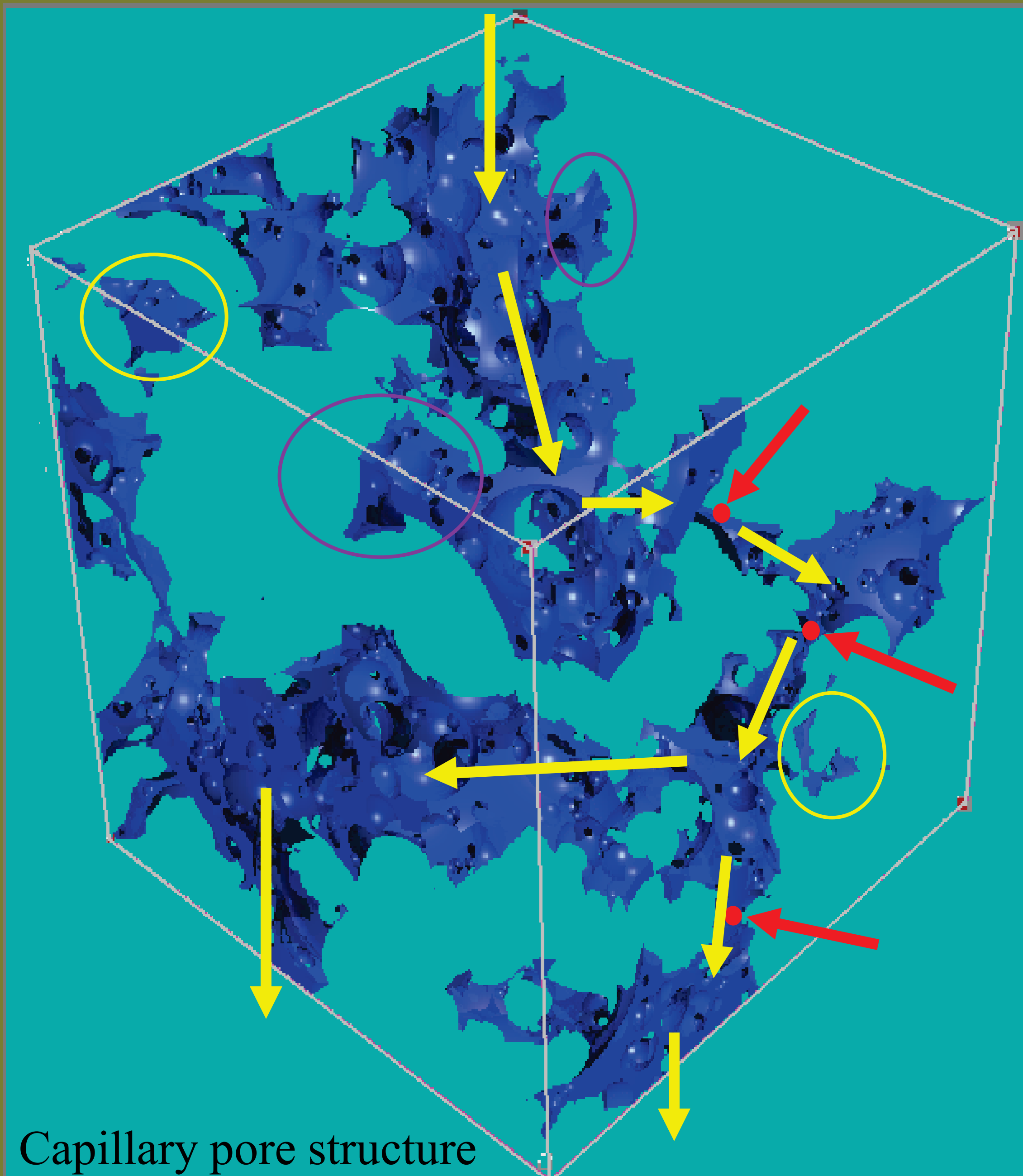
Qian, Z., Schlangen, E; Ye, G, et al (2010), Prediction of mechanical properties of cement at microscale, MATERIALES DE CONSTRUCCION., 60 297 P7-18

3D Pore Structure





3D simulated cement paste, Pore structure (w/c=0.35)

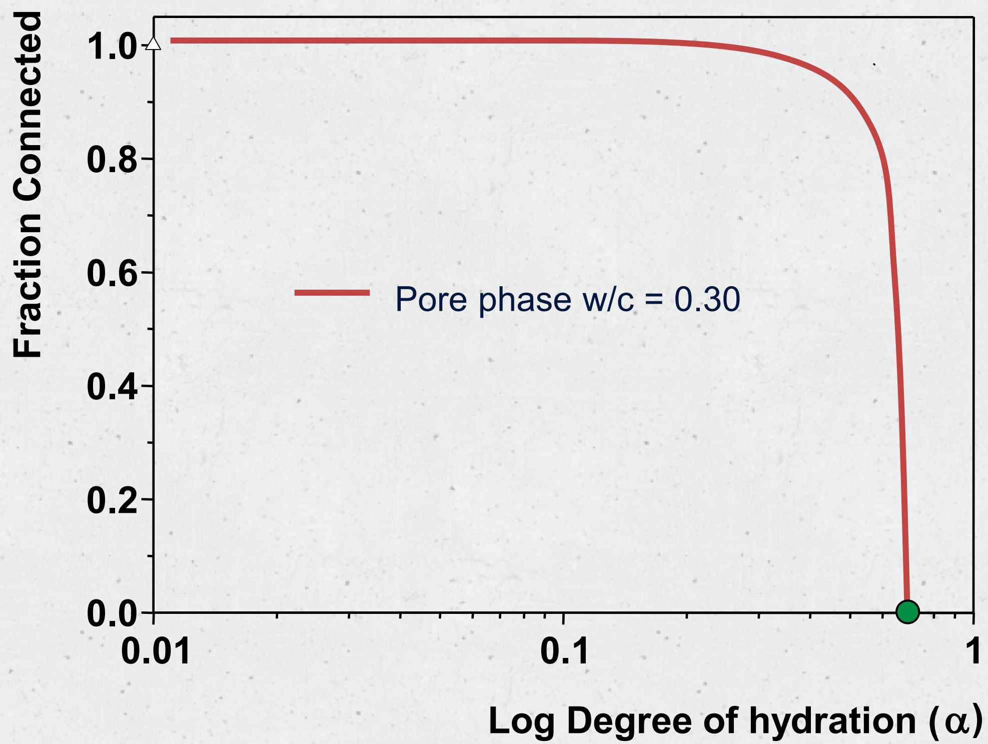


- Isolated pores
- Dead-end pores
- Critical link (necks)

Ye, G (2005). Percolation of capillary pores in hardening cement pastes. Cement and concrete research, 35, 167-176.

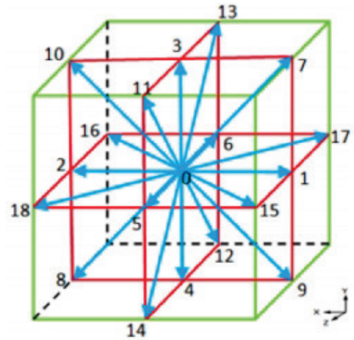
Connectivity of pore phase

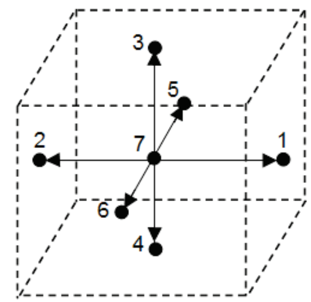
- De-percolation of capillary porosity



Ye, G (2005). Percolation of capillary pores in hardening cement pastes. Cement and concrete research, 35, 167-176.

Transport properties: Lattice Boltzmann Method





Micro-scale solver

PermLBS module
Multiple-relaxation-time lattice Boltzmann model
→ Permeability of cement-based materials at micro level

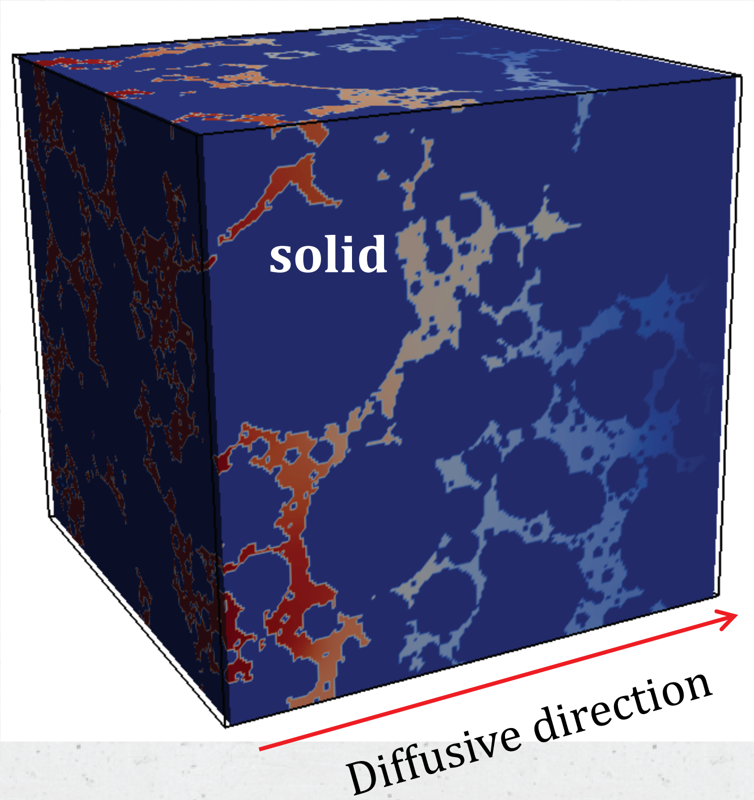
SCMPLBS module
Multi-phase lattice Boltzmann model
→ Moisture distribution in cement-based materials at micro level

DiffLBS module
Lattice Boltzmann model for diffusion
→ Ionic/gas diffusivity in cement-based materials at micro level

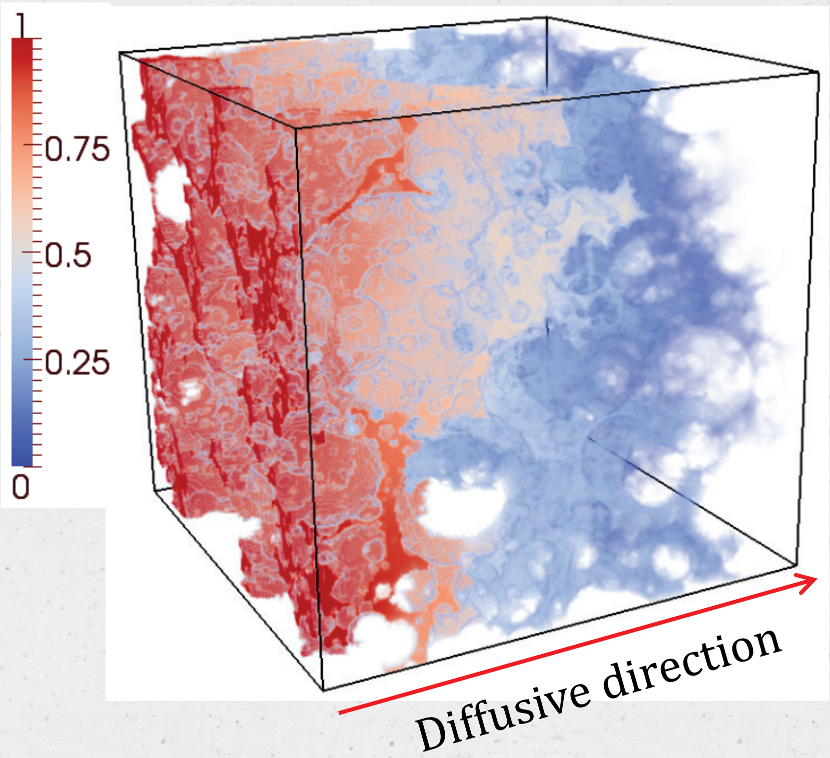
Mingzhong Zhang, Guang Ye, Klaas van Breugel, Modeling of ionic diffusivity in non-saturated cement-based materials using lattice Boltzmann method, Cement and Concrete Research, 42 (11), 2012, 1524-1533

DiffLBS Module: Diffusion in cement paste

(a)



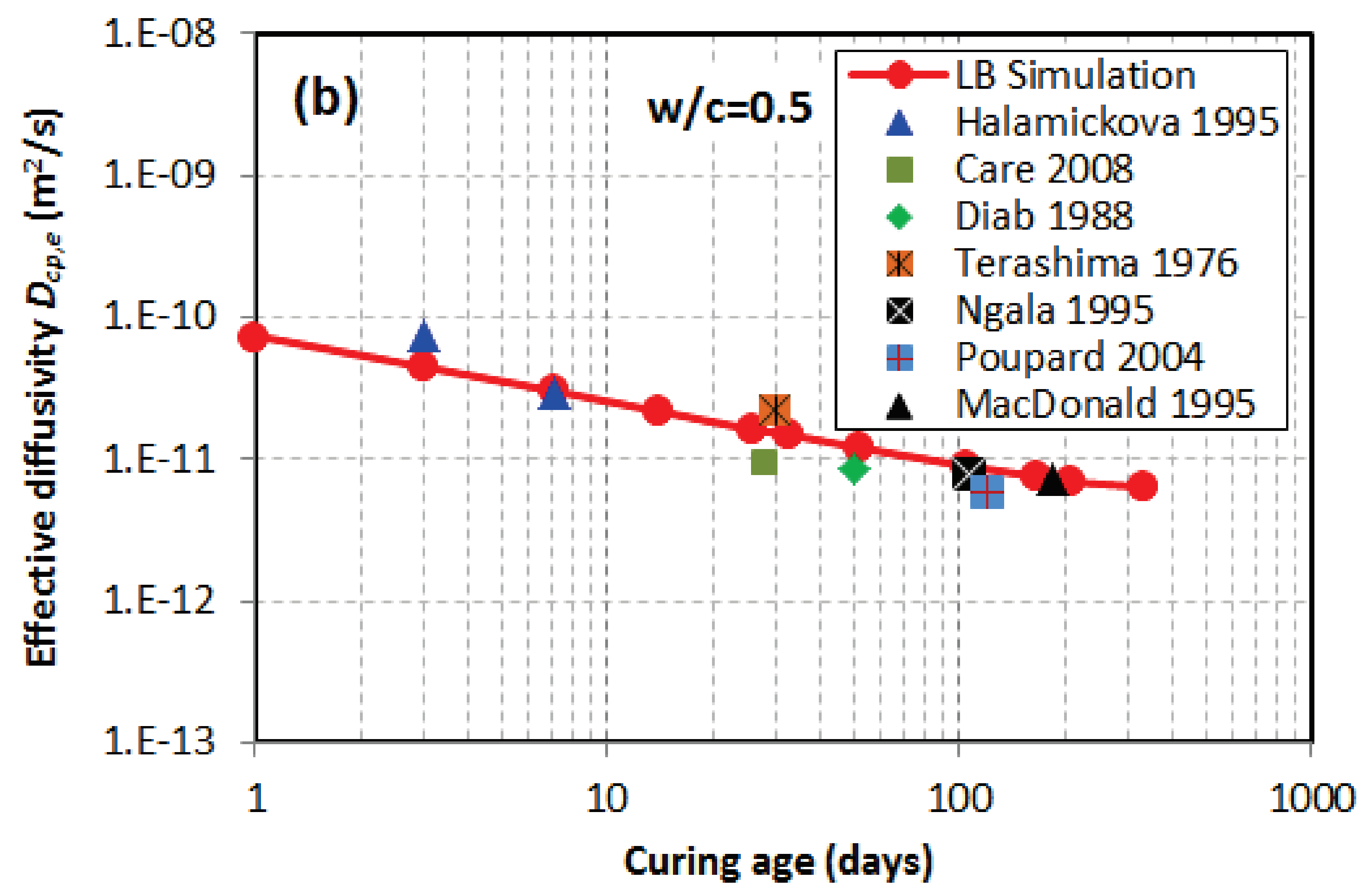
(b)



Concentration distribution of chloride ions in the connective pore structure of cement paste

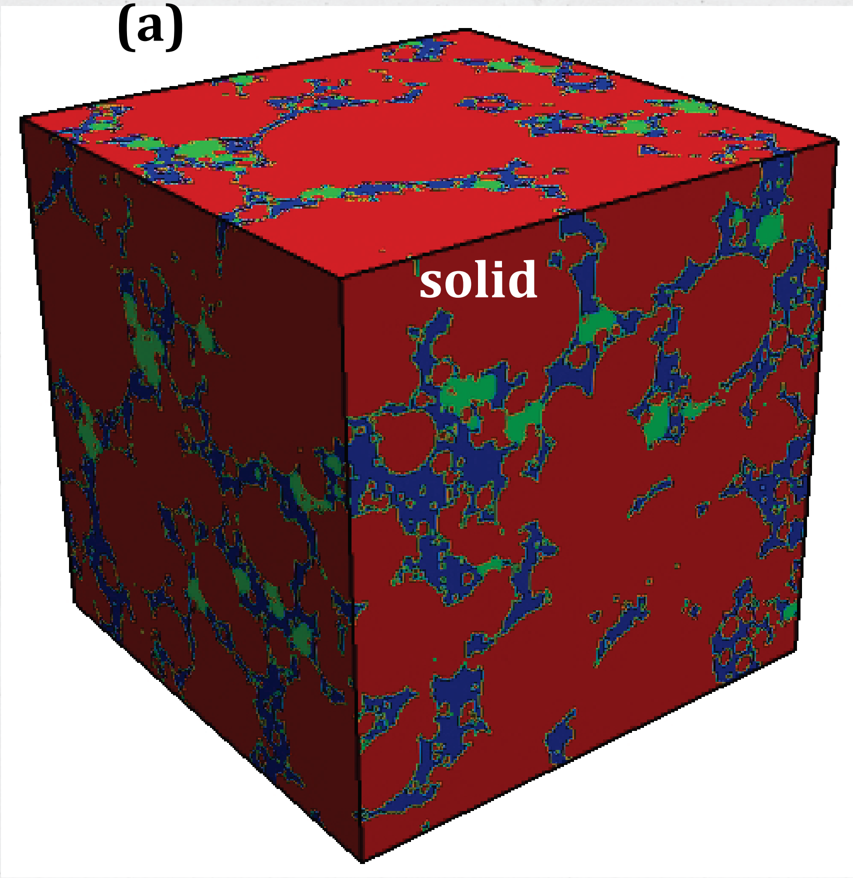
Mingzhong Zhang, Guang Ye, Klaas van Breugel, Modeling of ionic diffusivity in non-saturated cement-based materials using lattice Boltzmann method, Cement and Concrete Research, 42 (11), 2012, 1524-1533

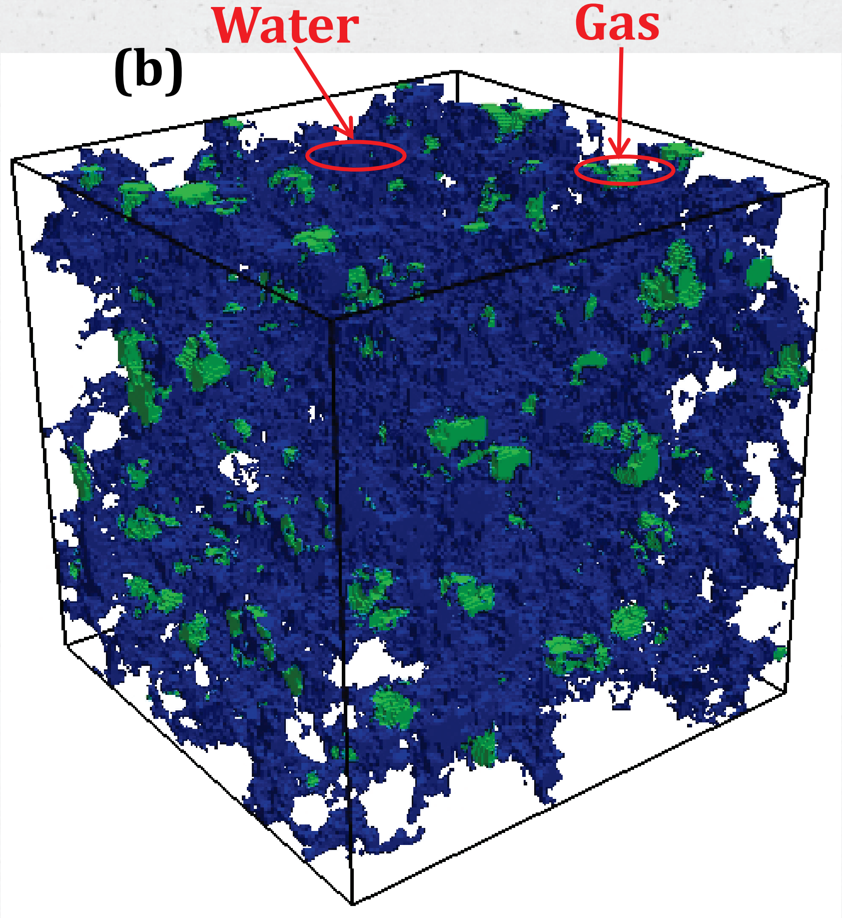
DiffLBS Module: Diffusion in cement paste



M Zhang, G Ye, K van Breugel (2014), Multiscale lattice Boltzmann-finite element modelling of chloride diffusivity in cementitious materials. Part II: Simulation results and validation, *Mechanics Research Communications* 58, 64-72 1

SCMPLBS Module (Moisture Distribution)

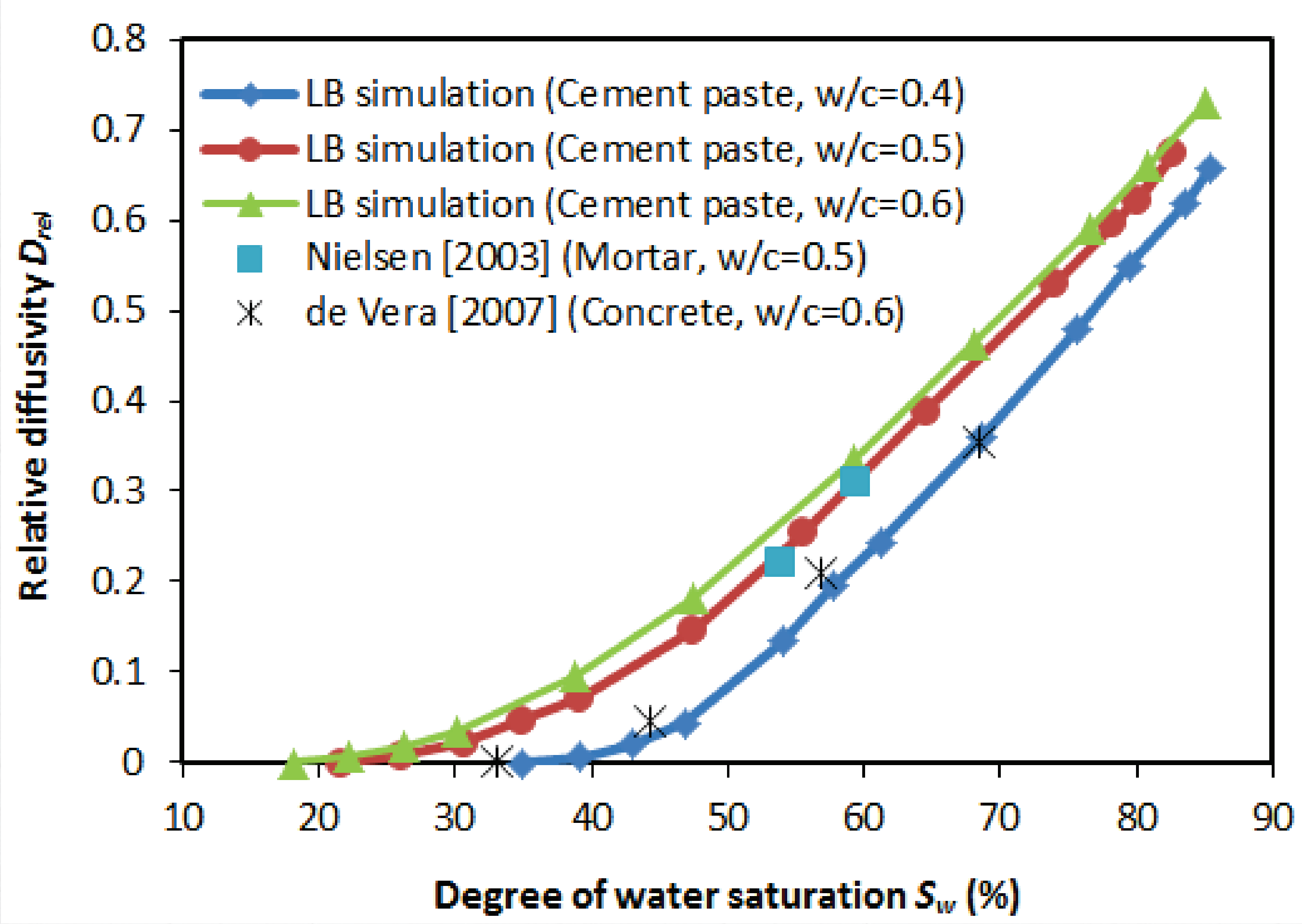




The equilibrium distribution of water-gas system with a degree of water saturation of 83% in the microstructure and pore structure of cement paste

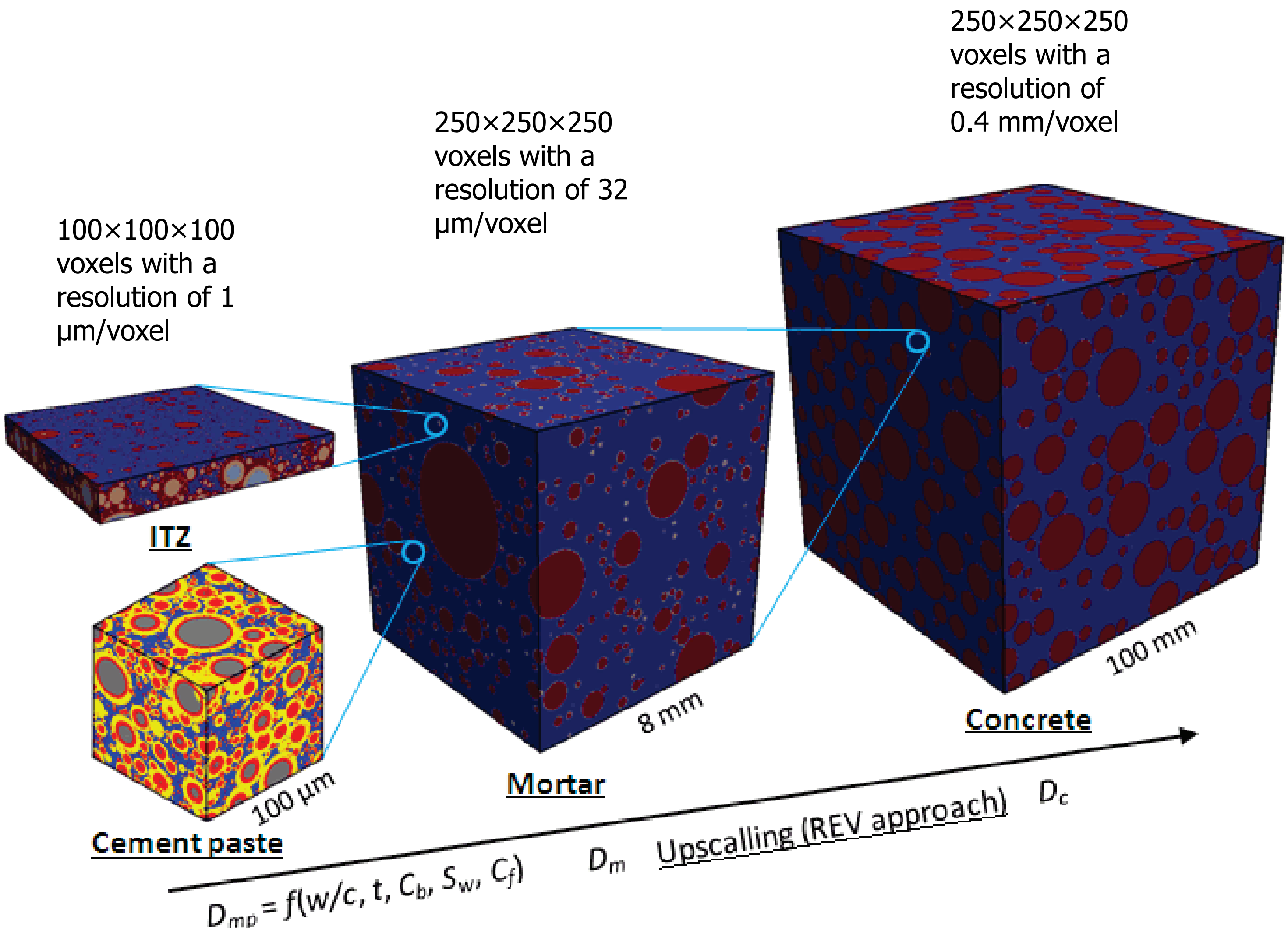
M Zhang, G Ye, K van Breugel (2014), Multiscale lattice Boltzmann-finite element modelling of chloride diffusivity in cementitious materials. Part I: Algorithms and implementation, *Mechanics Research Communications* 58, 53-63.

SCMPLBS Module (Relative Diffusivity)



M Zhang, G Ye, K van Breugel (2014), Multiscale lattice Boltzmann-finite element modelling of chloride diffusivity in cementitious materials. Part I: Algorithms and implementation, *Mechanics Research Communications* 58, 53-63.

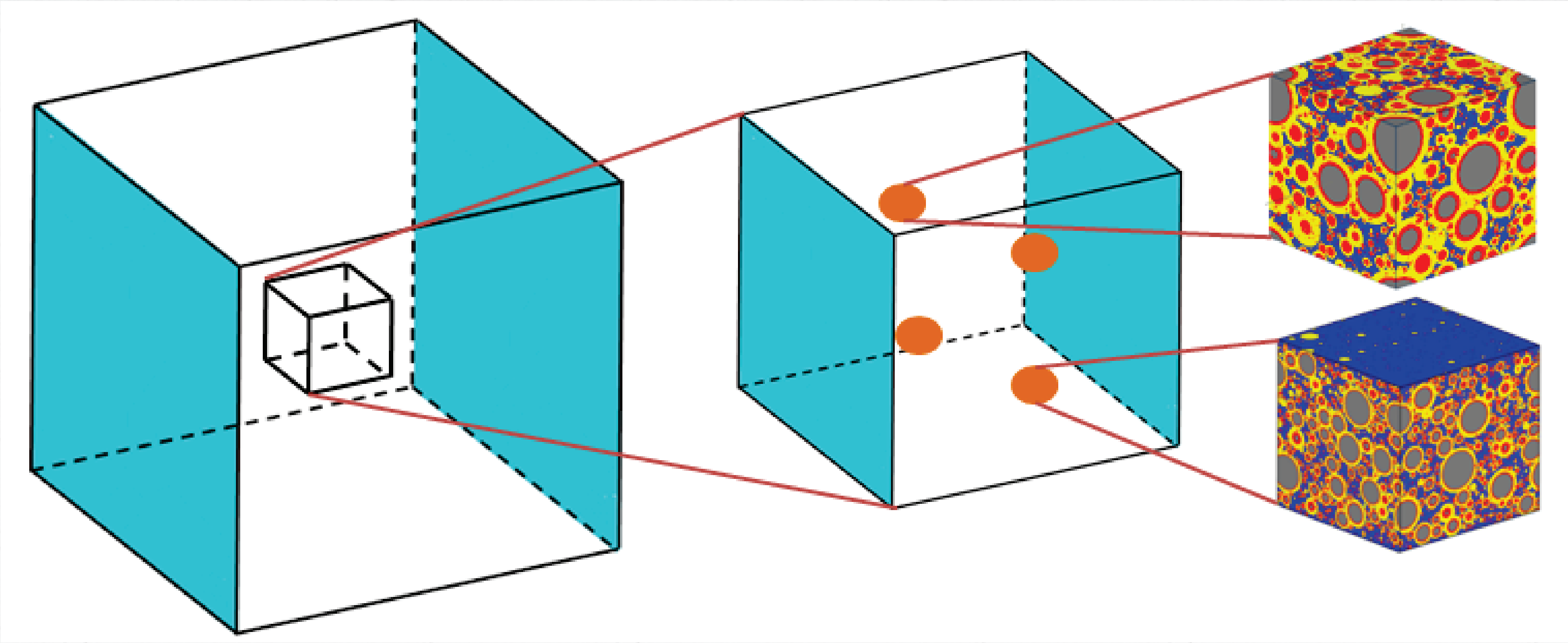
Multi scales simulation of concrete



M Zhang, G Ye, K van Breugel (2014), Multiscale lattice Boltzmann-finite element modelling of chloride diffusivity in cementitious materials. Part II: Simulation results and validation, *Mechanics Research Communications* 58, 64-72 1

Link different scales: Upscaling techniques

Volume averaging technique



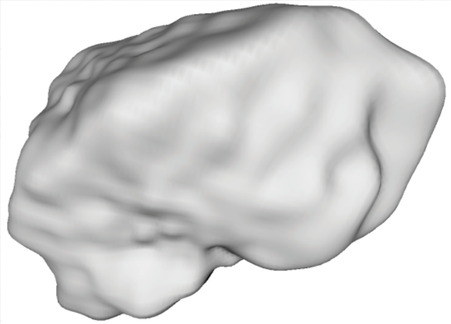
Concrete (cm) **Mortar (mm)** **Matrix (µm)**

M Zhang, G Ye, K van Breugel (2014), Multiscale lattice Boltzmann-finite element modelling of chloride diffusivity in cementitious materials. Part II: Simulation results and validation, *Mechanics Research Communications* 58, 64-72 1

The spherical harmonic expansion

$$r(\theta,\varphi) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} a_{nm} Y_{nm}(\theta,\varphi)$$

$$Y_{nm}(\theta,\varphi) = \sqrt{\frac{(2n+1)(n-m)!}{4\pi(n+m)!}} P_{nm}(cos\theta)\, e^{im\varphi}$$



An irregular shape sand particle described by spherical harmonics

Z Qian, EJ Garboczi, G Ye, E Schlangen, 2014, Anm: a geometrical model for the composite structure of mortar and concrete using real-shape particles, Materials and Structures, 1-10.

Contributor

- Klaas van Breugel
- Eddy Koenders
- Zhiwei Qian
- Qi Zhang
- Mingzhong Zhang
- Pen Gao

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MULTIPHYSICS MODELING OF CONCRETE HARDENING AND DURABILITY

Vít Šmilauer - Czech Technical University in Prague, Czech Republic

Karolina Hájková – Ibid.

Michal Hlobil – Ibid.

Czech Technical University in Prague

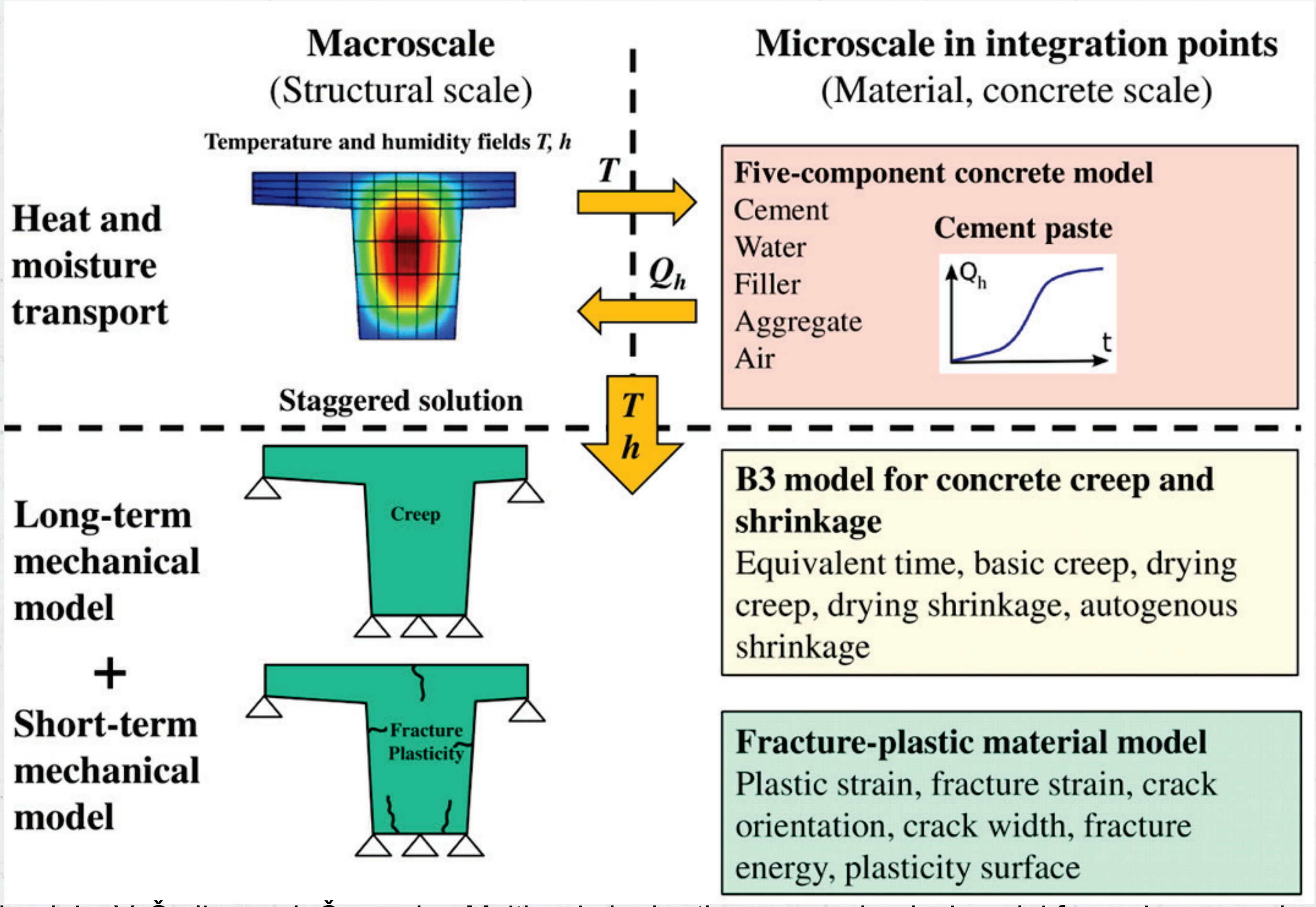
ATENA

Computed with OOFEM.ORG

Outline

- Multiscale framework of thermo-hygro-mechanical model
  - Heat and moisture transport
  - Creep and shrinkage model
  - Damage model and cracking
  - Validation
- Model for carbonation and chlorides including cracks
  - Formulation
  - Validation

Thermo-hygro-mechanical model



Microscale:
Affinity hydration model
Heat capacity
Thermal conductivity
Hydration heat
Water consumption

Macroscale:
Balance equations
Creep depends on moisture

[L. Jendele, V. Šmilauer, J. Červenka: Multiscale hydro-thermo-mechanical model for early-age and mature concrete structures. Advances in Engineering Software. 2014, vol. 72, p. 134-146.]

Affinity hydration model

- Modified model from Cervera et al., 1999
- 4 parameters

$$\tilde{A}_{25}(DoH) = B_1 \left(\frac{B_2}{DoH_\infty} + DoH \right) (DoH_\infty - DoH) \exp \left(-\bar{\eta} \frac{DoH}{DoH_\infty} \right)$$

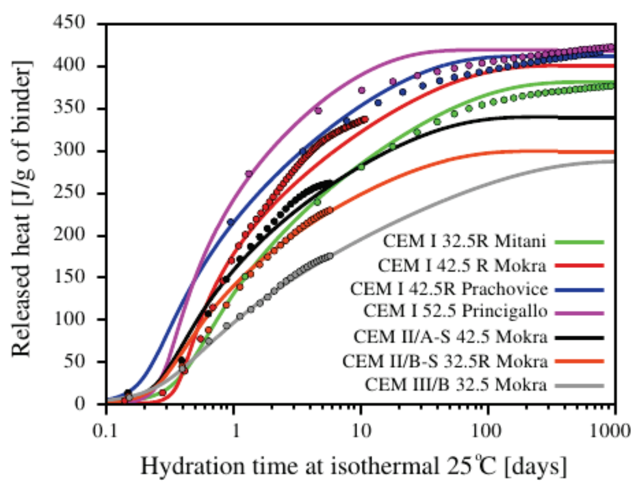
$$\tilde{A}_T = \tilde{A}_{25} \exp \left[\frac{E_a}{R} \left(\frac{1}{273.15 + 25} - \frac{1}{T} \right) \right]$$

$$\frac{\mathrm{d}\,DoH}{\mathrm{d}t} = \tilde{A}_T(DoH)\beta_\varphi,$$

$$\beta_\varphi(\varphi) = \left[1 + (a - a\varphi)^4 \right]^{-1}$$

$$Q(t) = Q_{pot}\alpha$$

$$w_n = 0.23c\alpha$$



[W. da Silva, V. Šmilauer, P. Štemberk: Upscaling semi-adiabatic measurements for simulating temperature evolution of mass concrete structures. Materials and Structures. 2015, vol. 48, no. 4, p. 188-197.]

Heat and moisture transport

- General mass balance equations

$$\frac{\partial H}{\partial t} = -\nabla \cdot q + Q_h$$ … heat

$$\frac{\partial w}{\partial t} = -\nabla \cdot J + Q_w$$ … moisture

- Künzel's heat/moisture coupled model

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + \frac{\partial Q_s}{\partial t} + h_v \nabla \cdot (\delta_p \nabla (h \cdot p_{sat}))$$

$$\frac{\partial w}{\partial h}\frac{\partial h}{\partial t} = \nabla \cdot (D_\varphi \nabla h + \delta_p \nabla (h \cdot p_{sat})) - w_n$$

Long-term mechanical material model

- Creep and shrinkage - B3 model

$$\varepsilon_t(t) = \int_0^t J(t,t',h,T)\,d\sigma(t') + \varepsilon_{sh}(t,t_0,h,T) + \varepsilon_T(T)$$

$$J(t,t',h,T) = q_1 + C_0(t,t',T) + C_d(t,t',t_0,h,T)$$

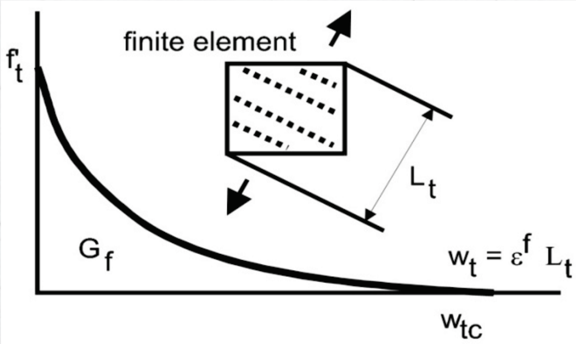
$$\Delta\boldsymbol{\sigma}_t = \mathbf{E}_t(\Delta\boldsymbol{\varepsilon}_t - \Delta\boldsymbol{\varepsilon}_t^{''})$$

- Effect of moisture on drying shrinkage and drying creep
- Effect of temperature on equivalent time

Short-term mechanical material model

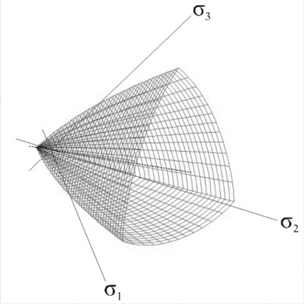
- Fracture-plastic model: orthotropic smeared crack model
- Strain decomposition

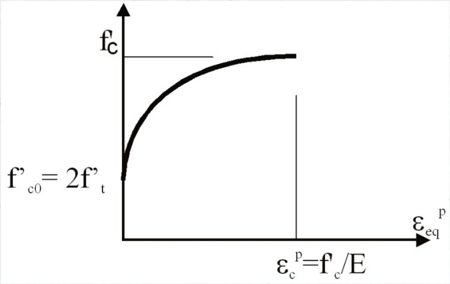
$$\dot{\sigma}_{ij} = D_{ijkl} \cdot (\dot{\varepsilon}_{kl} - \dot{\varepsilon}^{p}_{kl} - \dot{\varepsilon}^{f}_{kl})$$

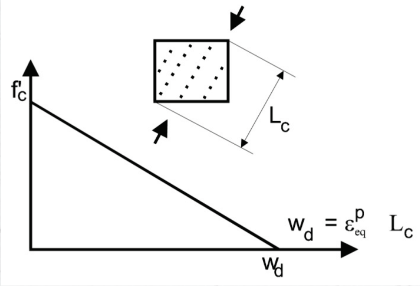


- Rankine criterion, Hordijk's softening law

- Crushing based on plasticity, Willam and Menetrey 3 parametric surface





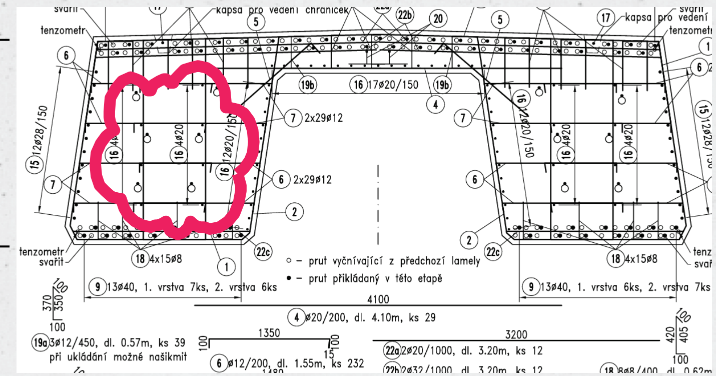


Validation – Oparno bridge

- Highway Prague – Dresden, 2008-2011, arch span 135 m

Arch's cross section close to abutment

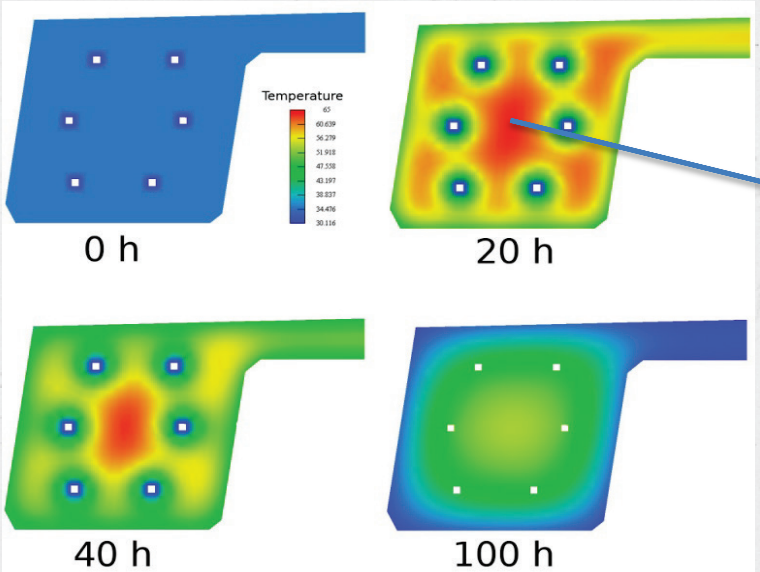
2.3 m

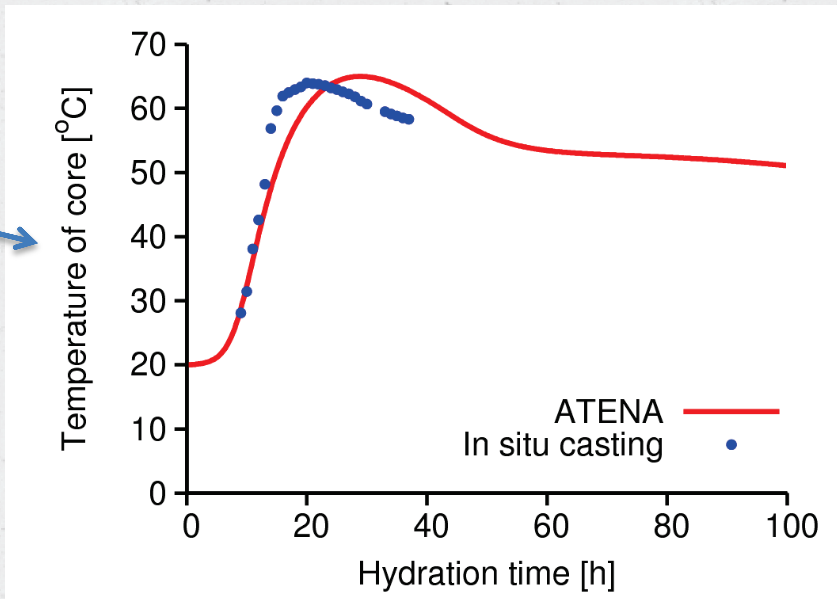


Width 7.0 m

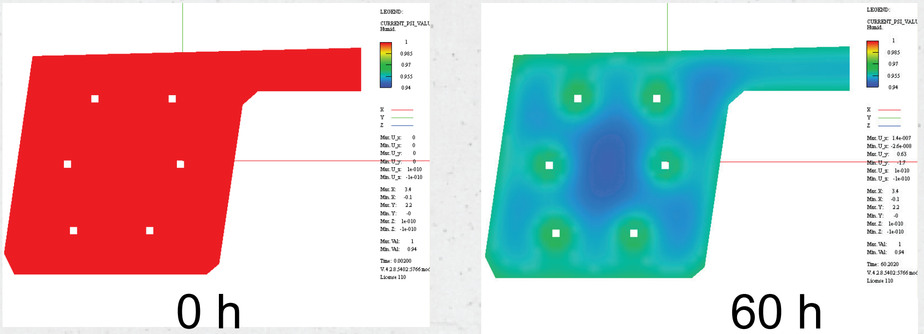
Validation – Oparno bridge

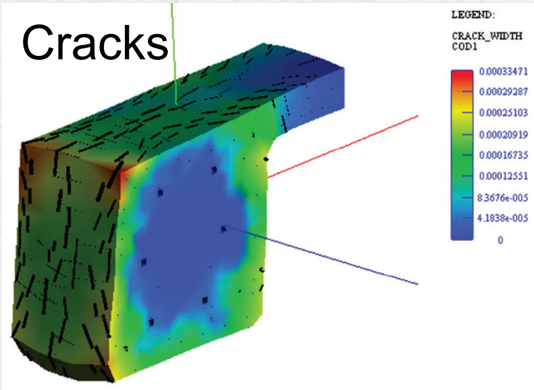
- Temperature field





- Relative humidity field





Carbonation

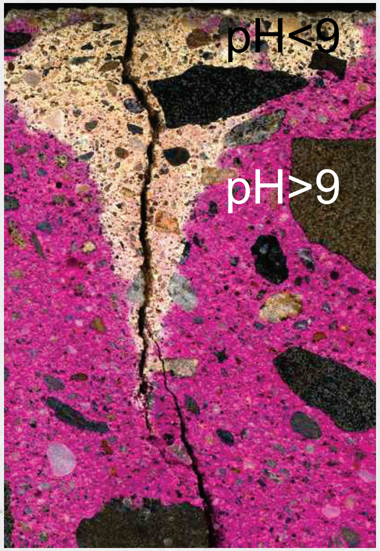
- Papadakis & Tsimas, 2002

$$x_c = \sqrt{\frac{2D_{e,CO_2}CO_2}{0.218(C+kP)}}\sqrt{t} = A_1\sqrt{t}$$

$$D_{e,CO_2} = 6.1 \cdot 10^{-6}\left(\frac{[W-0.267(C+kP)]/1000}{\frac{C+kP}{\rho_c}+\frac{W}{\rho_W}}\right)^3 \cdot (1-RH)^{2.2}$$

- Acceleration by cracking, Kwon & Na, 2011

$$x_c(t) = (2.816\sqrt{w}+1)A_1\sqrt{t}$$



[www.cmc-concrete.com]

Crack *w*idth (mm)	Concrete C=**400** kg/m3 P(fly ash)=50 kg/m3 w/b=0.45	Concrete C=**200** kg/m3 P=0 kg/m3 w/b=0.45
0	246 year	157 year
0.1	69.7 year	44.5 year
0.2	49.2 year	31.4 year
0.3	39.1 year	24.9 year

Chloride ingress

- 1D transient ingress

$$C(x,t) = C_s \left[1 - erf\left(\frac{x}{2\sqrt{D_m(t) f(w) t}}\right)\right]$$

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m$$

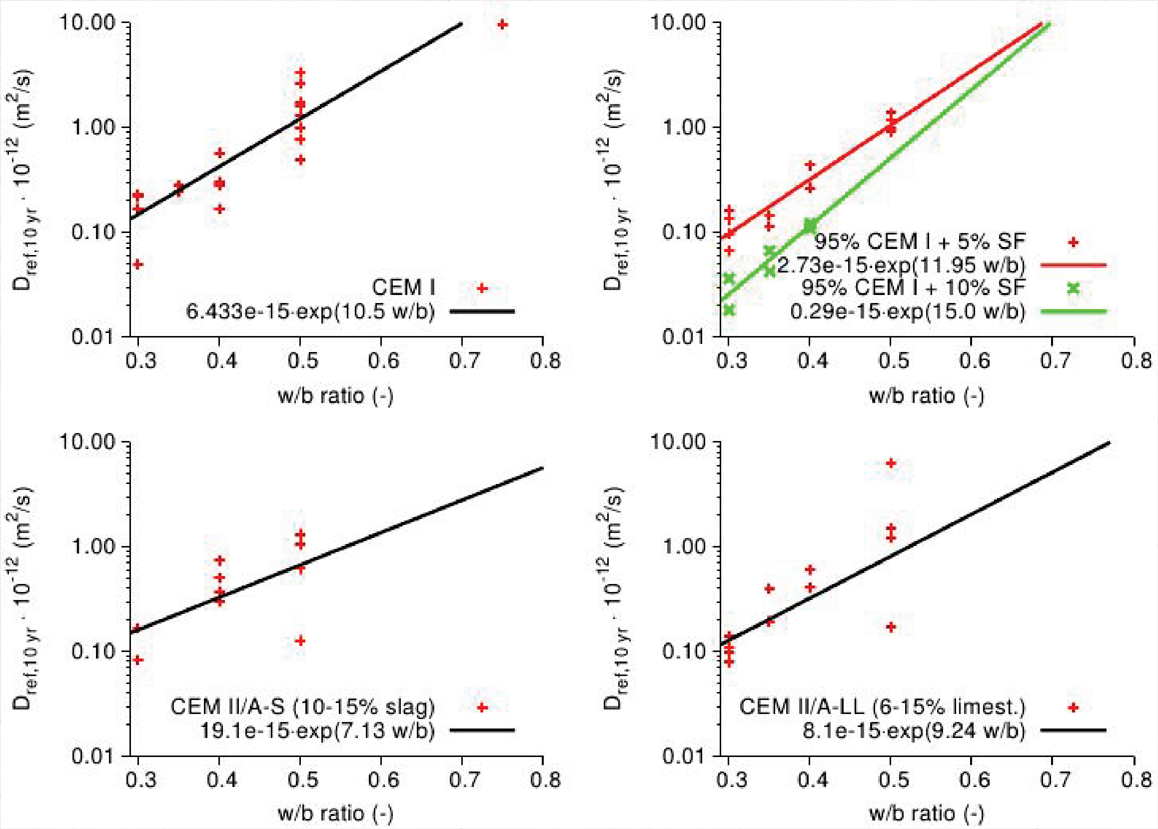
$$\begin{aligned} D_m(t) &= \frac{1}{t}\int_0^t D_{ref}\left(\frac{t_{ref}}{\tau}\right)^m \mathrm{d}\tau = \frac{D_{ref}}{1-m}\left(\frac{t_{ref}}{t}\right)^m, \quad t < t_R, \\ D_m(t) &= D_{ref}\left[1 + \frac{t_R}{t}\left(\frac{m}{1-m}\right)\right]\left(\frac{t_{ref}}{t_R}\right)^m, \quad t \geq t_R, \end{aligned}$$

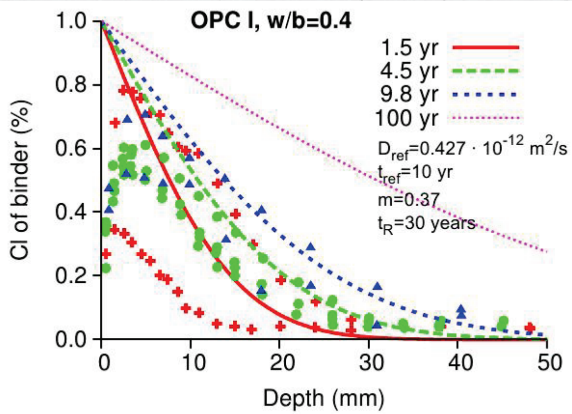
- Acceleration by cracking (Kwon, Na, Park, Jung, 2009)

$$f(w) = 31.61w^2 + 4.73w + 1$$

Chloride ingress and validation

- 10-year exposure in highway environment (Luping & Utgennant, 2007)



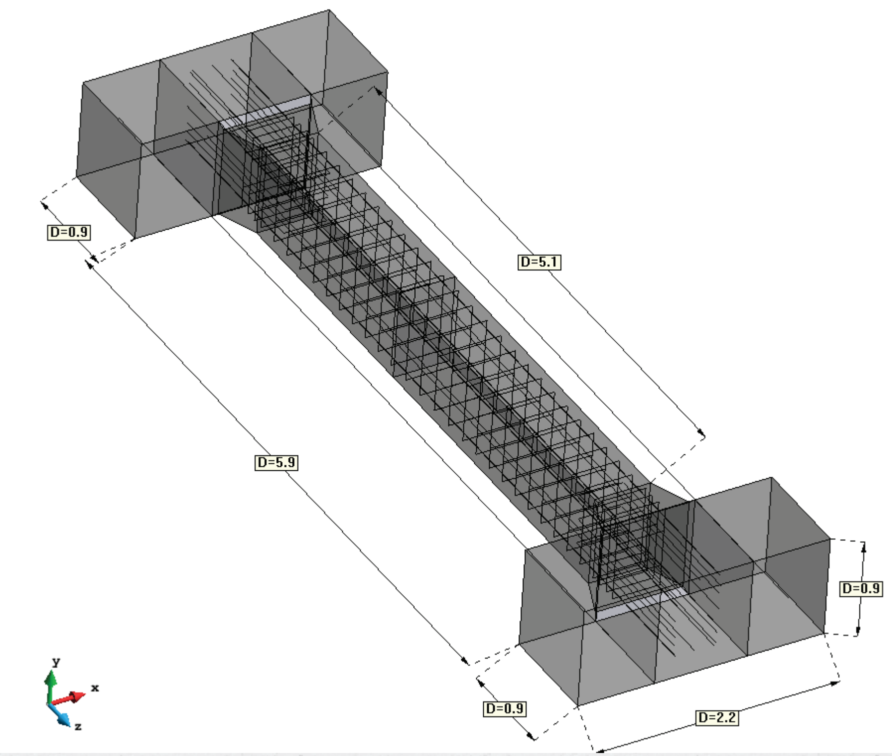


Crack width (mm)	Concrete w/b=0.55
0	74.58 year
0.1	36.02 year
0.2	15.70 year
0.3	7.76 year

ConCrack RG8 - Validation

- Restrained shrinkage

http://cheops.necs.fr/



[V. Červenka, J. Červenka, L. Jendele, V. Šmilauer, V.: ATENA simulation of crack propagation in CONCRACK benchmark. European Journal of Environmental and Civil Engineering. 2014, vol. 18, no. 7, p. 828-844.]

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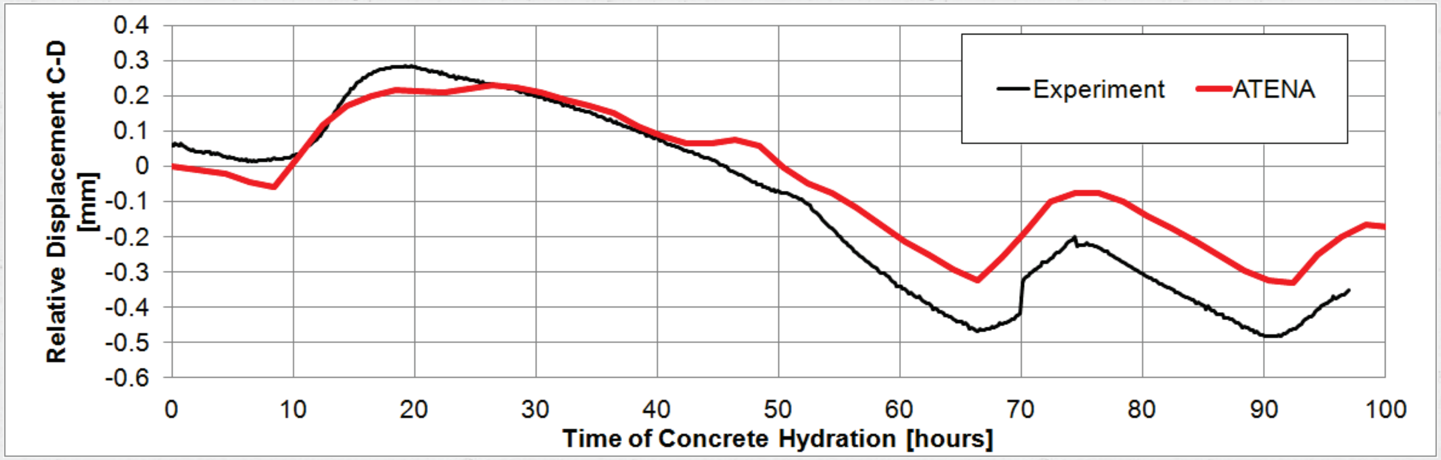
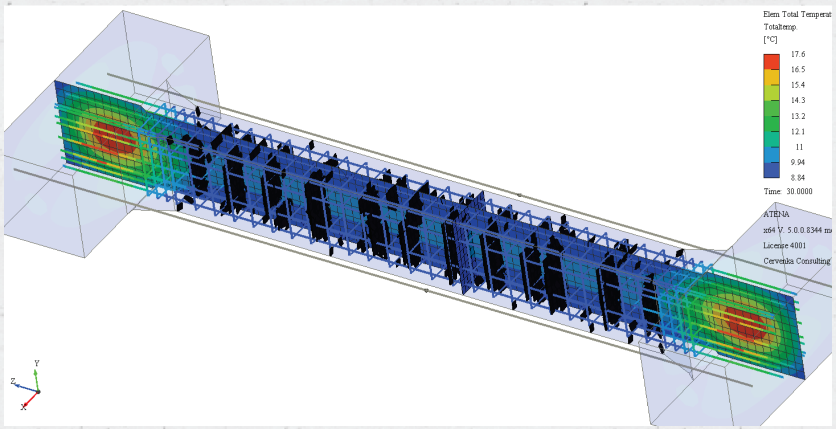
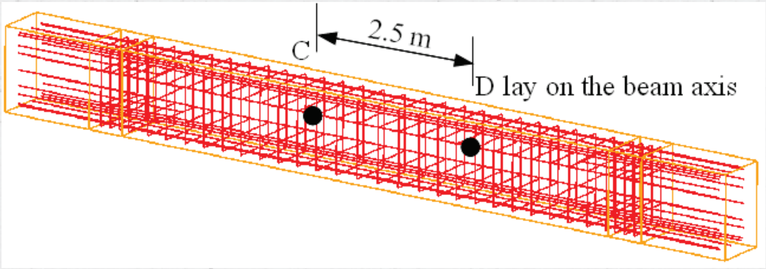
ConCrack RG8 - Validation

- Relative displacement C-D

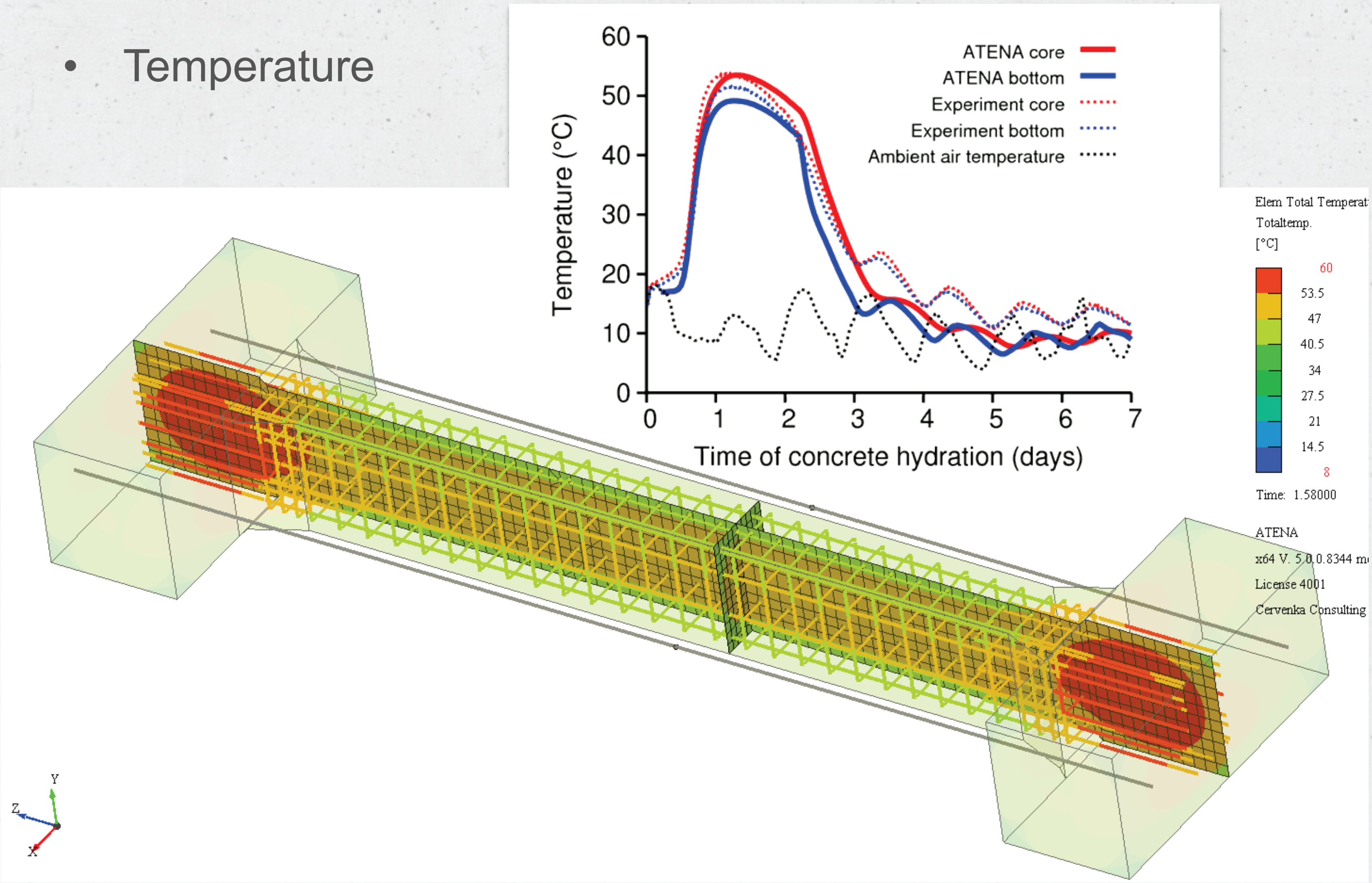






ConCrack RG8 - Validation

- Temperature



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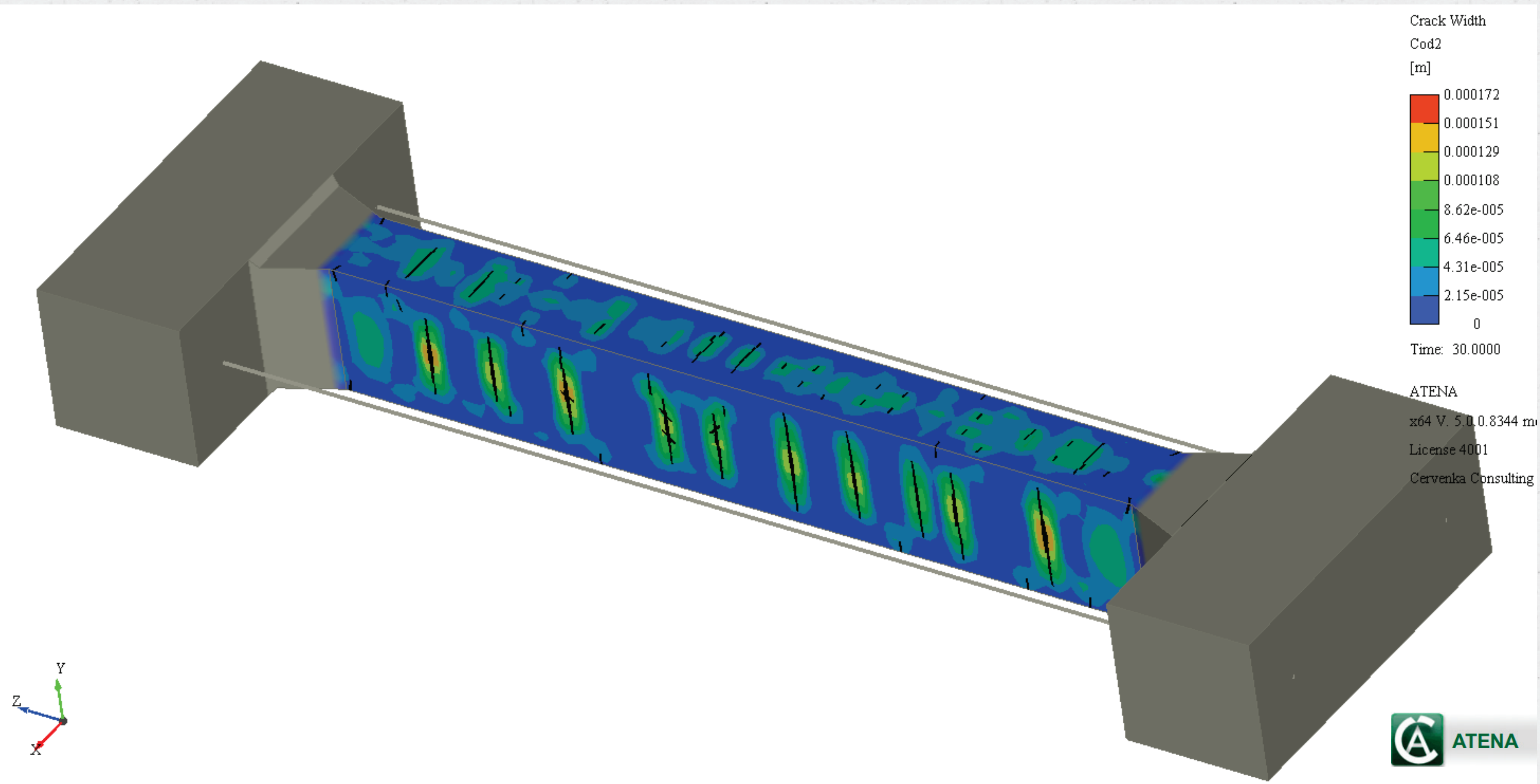
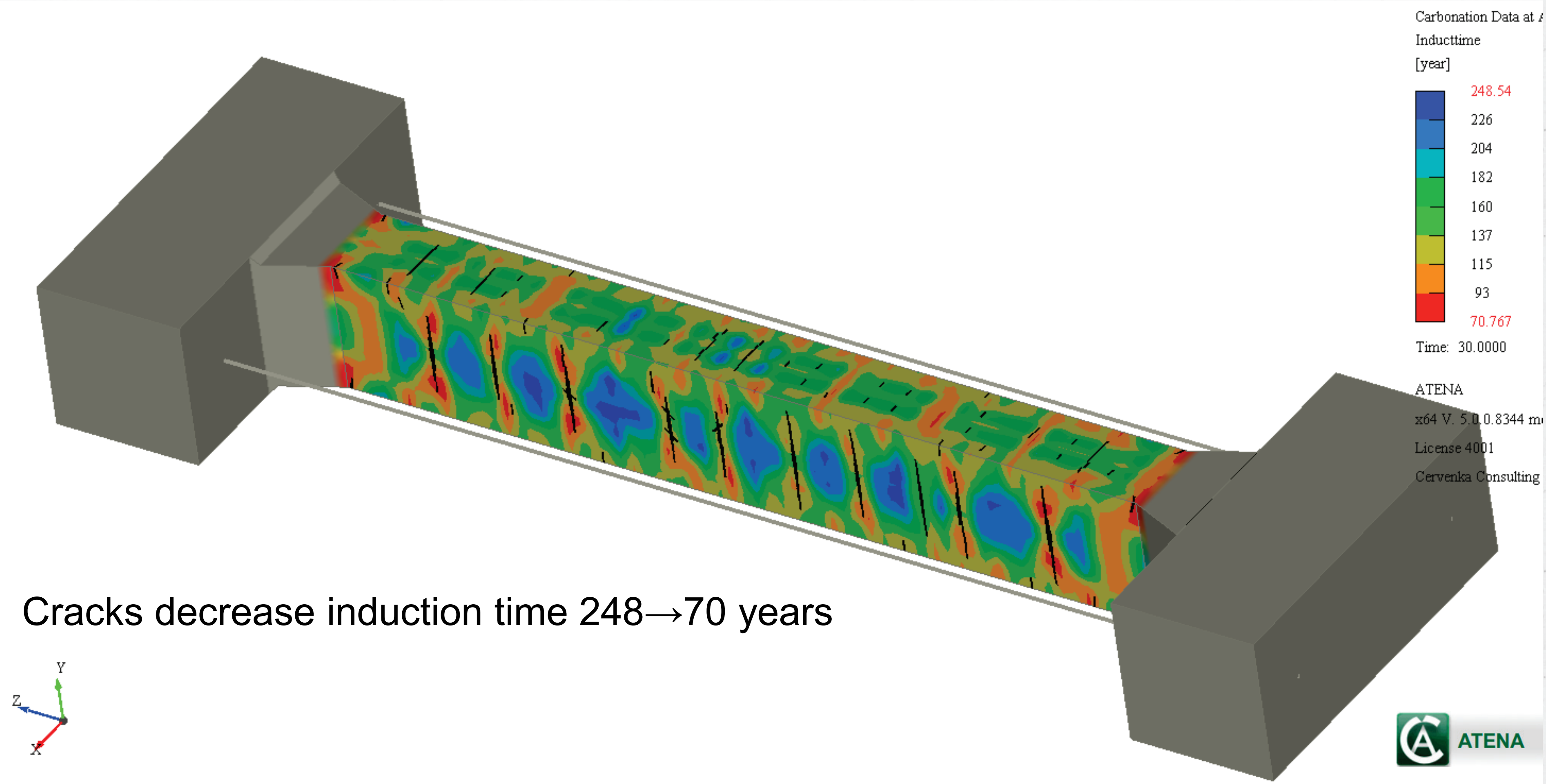
ConCrack RG8 - Validation

- Cracks at 30 days



ConCrack RG8 - Carbonation

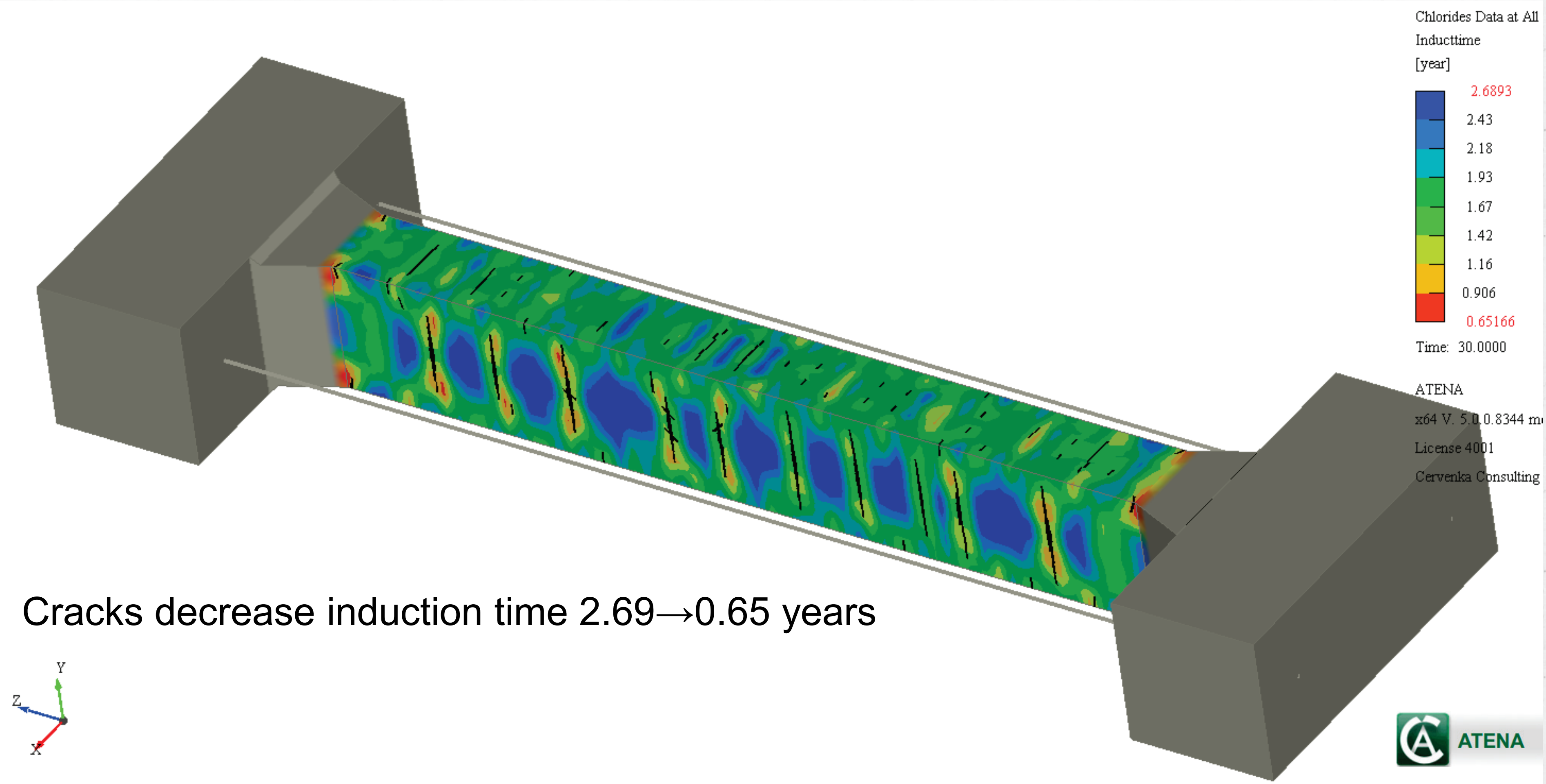
- Induction time for carbonation (70% RH)



Cracks decrease induction time 248→70 years

ConCrack RG8 – Chloride ingress

- Induction time for chlorides (30 mm cover, marine environment)



Cracks decrease induction time 2.69→0.65 years

Conclusions

- Thermo-hygro-mechanical model
  - Affinity hydration model
  - Prediction of crack width
- Cracks 0.3 mm decrease induction time about 6x

- Synergy within TU1404 working groups
  - WG1 – Material Parameters
  - WG2 – Benchmarking, multiscale models
  - WG3 – Crack mitigation, recommendations, sensitivity analysis

Acknowledgement
J. Červenka, V. Červenka, L. Jendele
Internal CTU project SGS15/030/OHK1/1T/11

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MICROMECHANICAL STUDIES OF DELAYED DEFORMATIONS AND DAMAGE OF CONCRETE

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GeM Institut de Recherche en Génie Civil et Mécanique
CNRS

SUMMARY

- Introduction
- Experimental and numerical methods
- Analysis of the creep of concrete at early ages
- Conclusion and perspectives

INTRODUCTION

Concrete structures cast in place are subjected to high loads at early ages. The effect of such loads, particularly in terms of creep deformation, is very significant in the following cases:

Underground structures (due to the soil pressure)

High buildings

Reinforced or prestressed concrete structures

Creep is very complex !!

☺ **Stresses relaxation due to restrained shrinkage when in traction**
☹ **Prestress loss even if linear**
☹ **Important settlements in high building**
☹ **Negative effects when coupled with microcracking (creep-damage coupling)**

At 1 month: is concrete damaged or sound?

INTRODUCTION

Last studies

Studies on the creep of mature concrete (compression, tension, flexural) (Ghosh 1974, Bazant et al.,88; Bissonnette et al.,95; Sanahuja et al., 09; Omar, 04; Reviron, 09; Saliba, 2012, etc)

Studies on the creep of young concrete
✓In compression: (Delahaie, 97; Jiang et al., 14, …)
✓In tension: (Atrushi, 03; Østergaard et al., 01; Briffaut, 10, etc)

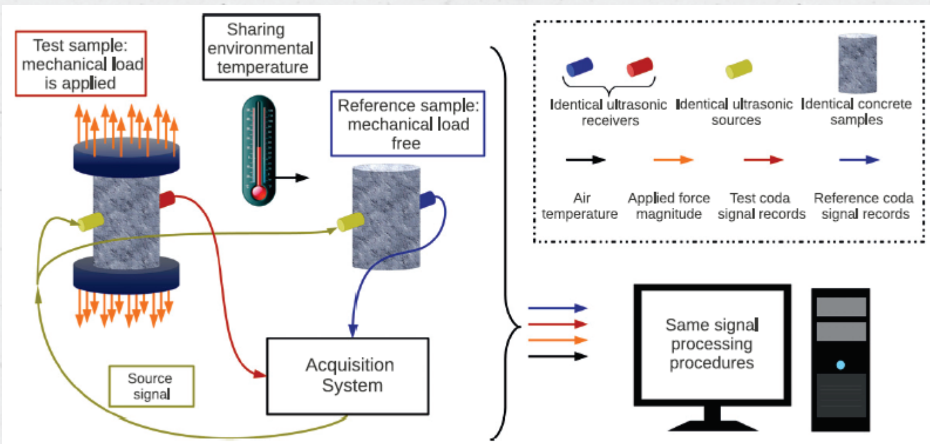
No work on the flexural *creep* of *young* concrete*!!!*

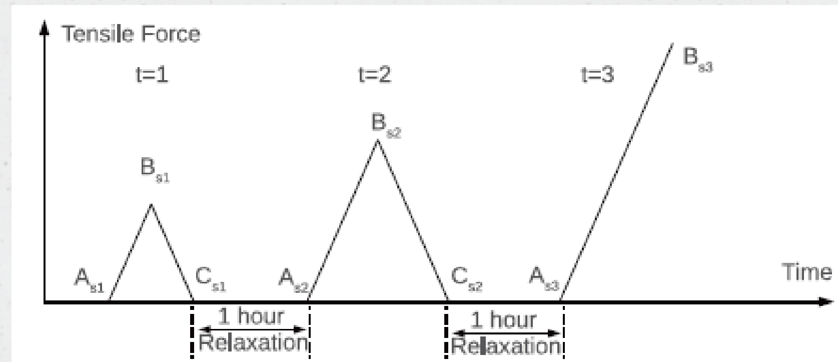
With low creep loading rates (<30% of the strength), mature concrete has a linear viscoelastic behaviour. But what about at early ages?

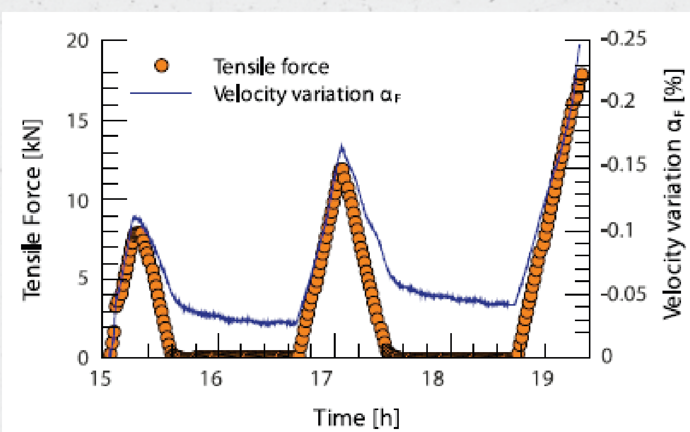
INTRODUCTION

Does microcracking occur at low loading?

Zhang, Abraham, Grondin, Loukili, Tournat, Le Duff, Lascoup, Durand, Ultrasonics, 2012





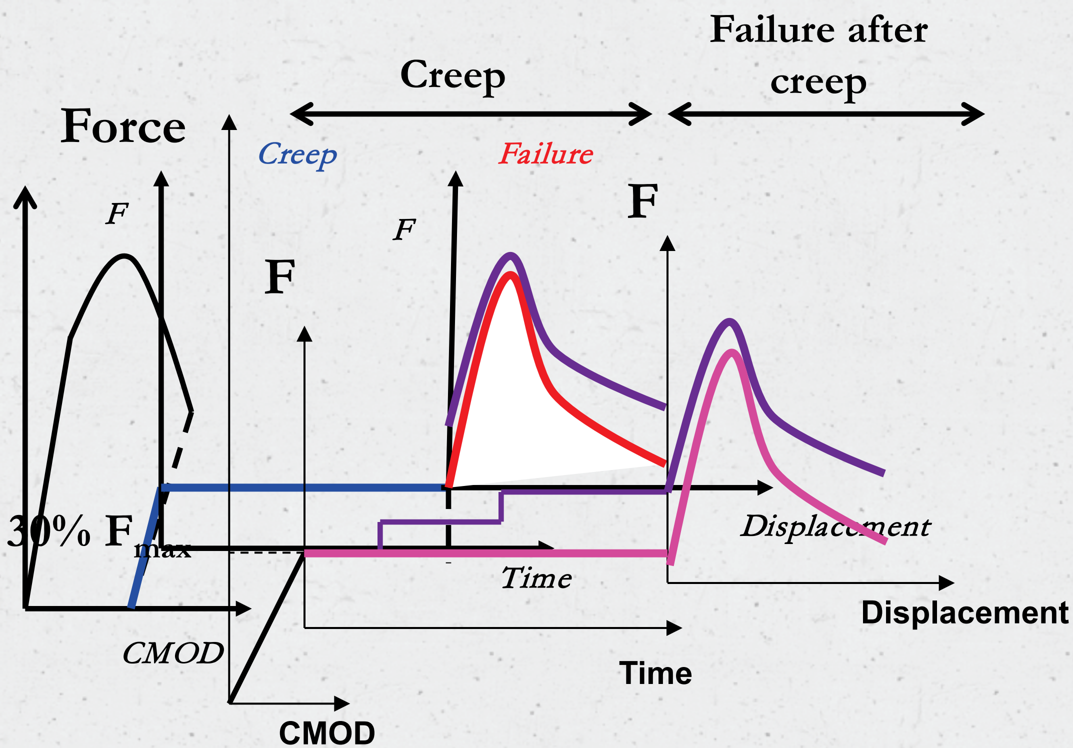


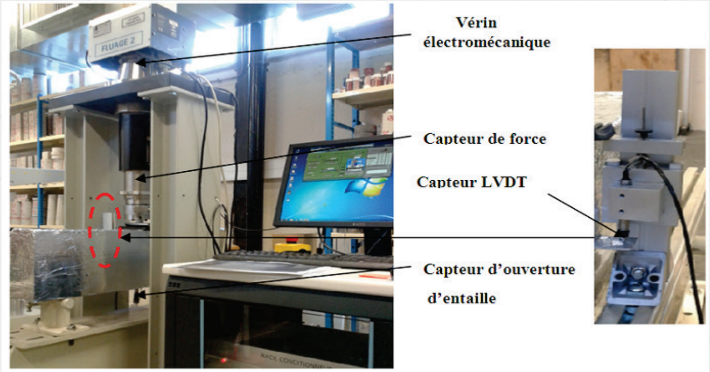
A portion of the velocity reduction remains within the concrete body and accumulates after each loading test

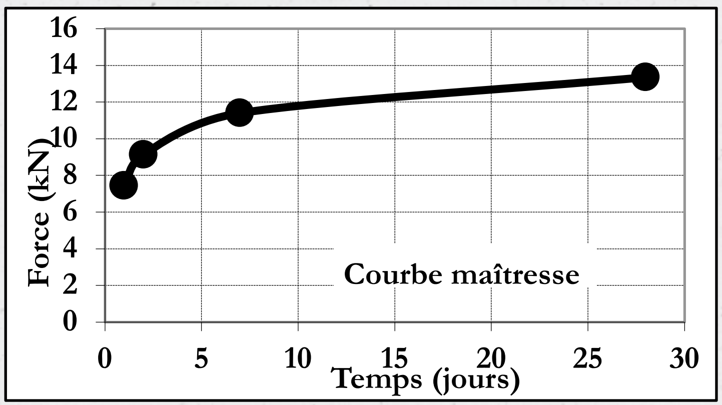
EXPERIMENTAL AND NUMERICAL METHODS

Creep and failure methods

Competition between solidification and creep

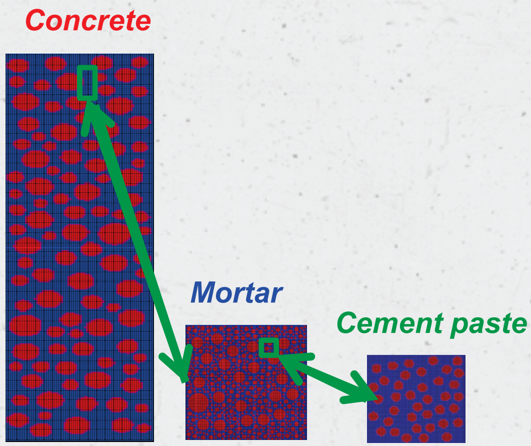






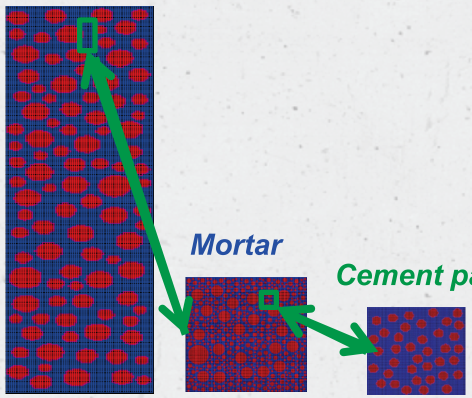
EXPERIMENTAL AND NUMERICAL METHODS

Multiscale model



EXPERIMENTAL AND NUMERICAL METHODS

Multiscale model



- The solidification theory (Bazant 1977)
  - So in a visco-elastic model the viscous parameters of CSH has maintained constant.

- The solidification theory is adopted at a early ages !
  - How to consider the influence of the porosity on the viscous behaviour of CSH?

EXPERIMENTAL AND NUMERICAL METHODS

Multiscale model

$C_3S + 5.3H \rightarrow CSH + 1.3CH$
$C_2S + 4.3H \rightarrow CSH + 0.3CH$
$C_3A + 6H \rightarrow C_3(A,F)H_6$
$C_4AF + 10H \rightarrow C_3(A,F)H_6 + FH_3 + CH$
$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32}$
$C_4AF + 3C\bar{S}H_2 + 30H \rightarrow C_6A\bar{S}_3H_{32} + FH_3 + CH$
$2C_3A + C_6A\bar{S}_3H_{32} + 4H \rightarrow 3C_4A\bar{S}H_{12}$
$2C_4AF + C_6A\bar{S}_3H_{32} + 12H \rightarrow 3C_4A\bar{S}H_{12} + 2FH_3 + 2CH$

Bernard, Ulm, Lemarchand, 2003

Residual water and saturation -> porosity

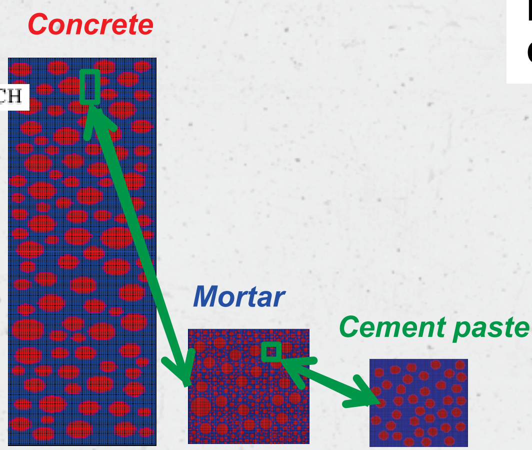
$$V_E(t) = V_{E0} - \sum V_E^X \xi_X(t)$$

with $V_E^X = V_{C0}\dfrac{n_E \rho_C f_X / \mathcal{M}_X}{n_X \rho_E / \mathcal{M}_E}$

Hydrates volume:

$$V_i^P(t) = \sum_{j=1}^{n} C_i^j \xi_j(t)$$

with $C_i^j = V_{C0}\dfrac{n_i^R \rho_C f_j / \mathcal{M}_j}{n_j^P \rho_i / \mathcal{M}_i}$



- ❑ **The solidification theory (Bazant 1977)**
  ➢ **So in a visco-elastic model the viscous parameters of CSH has maintained constant.**

- ❑ **The solidification theory is adopted at a early ages !**

  ➢ **How to consider the influence of the porosity on the viscous behaviour of CSH?**

The material is defined by a representative volume and an effective viscoelastic behaviour calculated by homogenization of a viscoelastic matrix and elastic inclusions

(Ricaud and Masson, 2009)

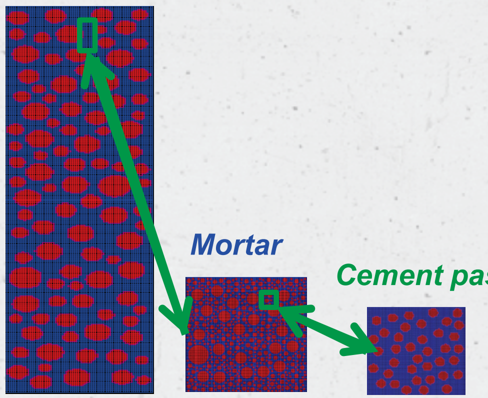
$$\left\langle \bar{\bar{\varepsilon}}^{v}(t,\bar{y}) \right\rangle_V = \bar{\bar{\bar{\bar{J}}}}^{hom}(t) : \left\langle \bar{\bar{\sigma}}(t,\bar{y}) \right\rangle_V$$

$$k^i_{car} = \frac{3.A(fp).k^i_{fp}}{4}$$

EXPERIMENTAL AND NUMERICAL METHODS

Multiscale model

Step 1: Inverse approach to determine the « characteristic » visco-elastic parameters of CSH



$$\left\langle \overline{\overline{\varepsilon}}^{v}(t,\overline{y}) \right\rangle_V = \overline{\overline{\overline{\overline{J}}}}^{\text{hom}}(t) : \left\langle \overline{\overline{\sigma}}(t,\overline{y}) \right\rangle_V$$

(Ricaud and Masson, 2009)

$$k^{i}_{car} = \frac{3.A(fp).k^{i}_{fp}}{4}$$

Step 2: Study on the age influence due to the porosity evolution on the creep of concrete

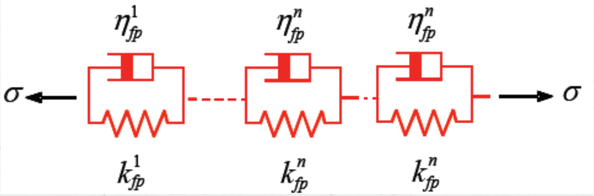
Step 3: Operating model for the analysis of the flexural creep at early ages

EXPERIMENTAL AND NUMERICAL METHODS

Multiscale model

- Coupling between visco-elasticity and damage $\underline{\underline{\sigma}}(\underline{y}) = \underset{\sim}{C}(\underline{y}, \underline{\underline{\varepsilon}}(\underline{y})) : (\underline{\underline{\varepsilon}}(\underline{y}) - \underline{\underline{\varepsilon}}^{fp}(\underline{y}))$

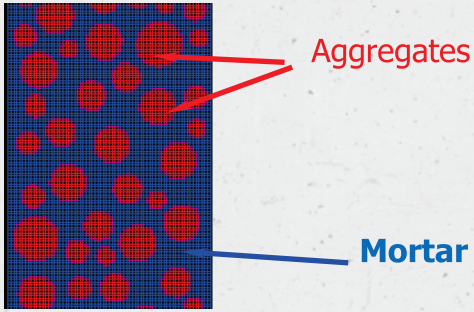
- Kelvin-Voigt model with 3 chains $\eta^i_{fp} \dot{\underline{\underline{\varepsilon}}}^i_{fp}(t) + k^i_{fp} \underline{\underline{\varepsilon}}^i_{fp}(t) = \underline{\underline{\tilde{\sigma}}}(t)$



- Damage evolution $d = 1 - \frac{\varepsilon_{d0}}{\varepsilon_{eq}} \exp\left[B_t(\varepsilon_{d0} - \varepsilon_{eq})\right]$

with $\varepsilon_{eq} = \sqrt{\langle \varepsilon^e \rangle_+ : \langle \varepsilon^e \rangle_+ + \beta \langle \varepsilon^v \rangle_+ : \langle \varepsilon^v \rangle_+}$

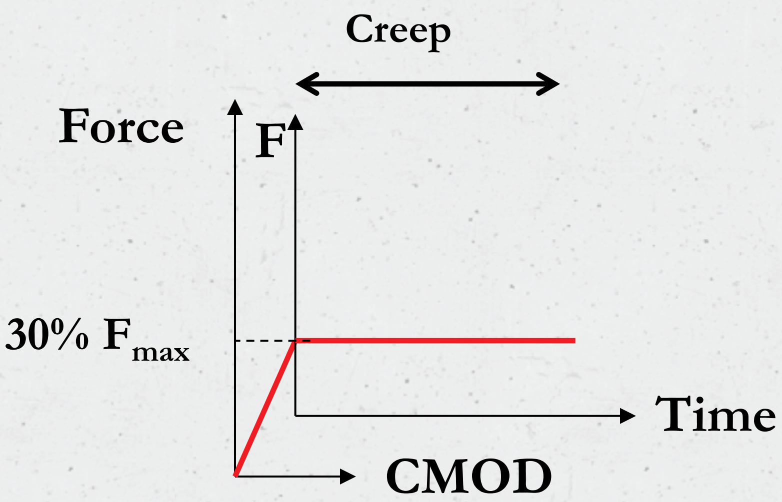
[Mazzotti et Savoia, 2003]
[Saliba et al., 2013]

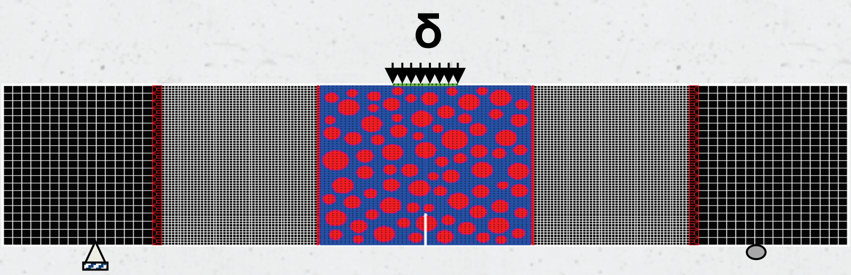


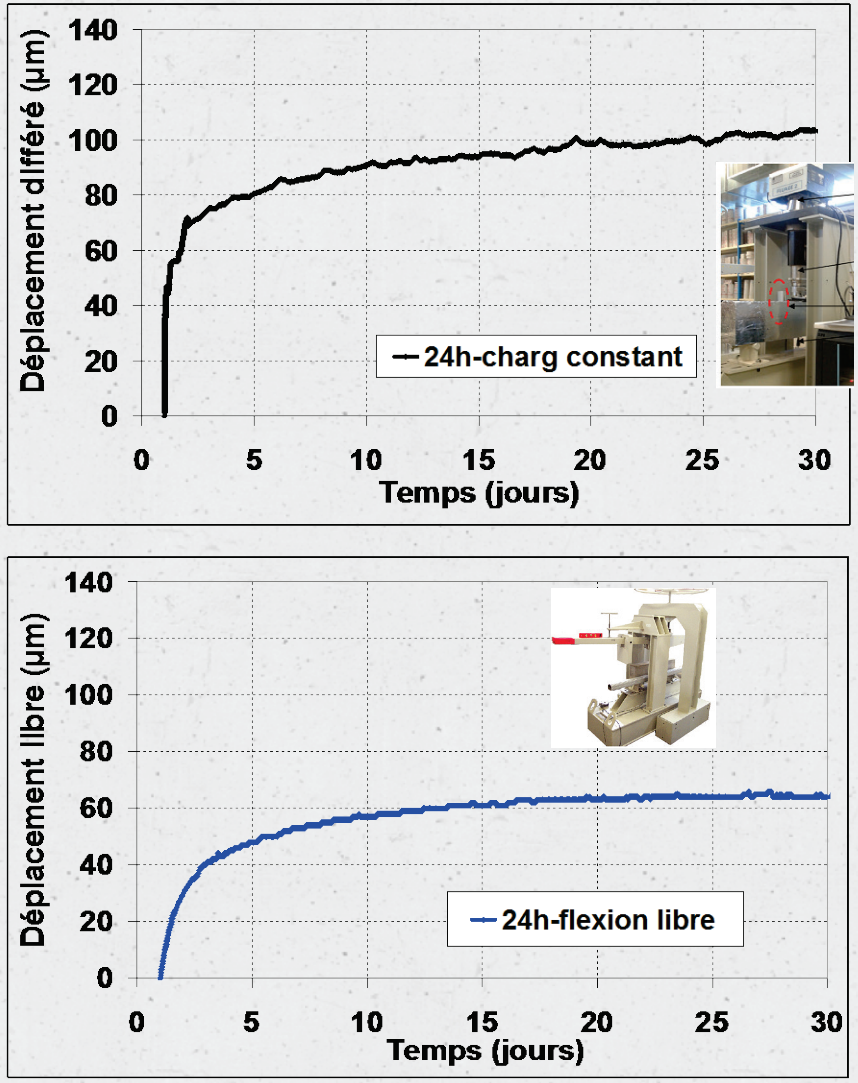
Saliba, Grondin, Matallah, Loukili, Boussa, *Mech Time Depend Mat*, 2013

ANALYSIS OF THE CREEP OF CONCRETE

Multiscale modelling of the creep tests

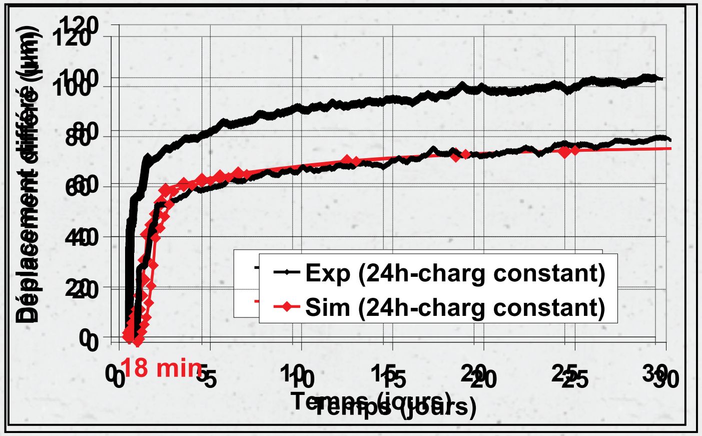


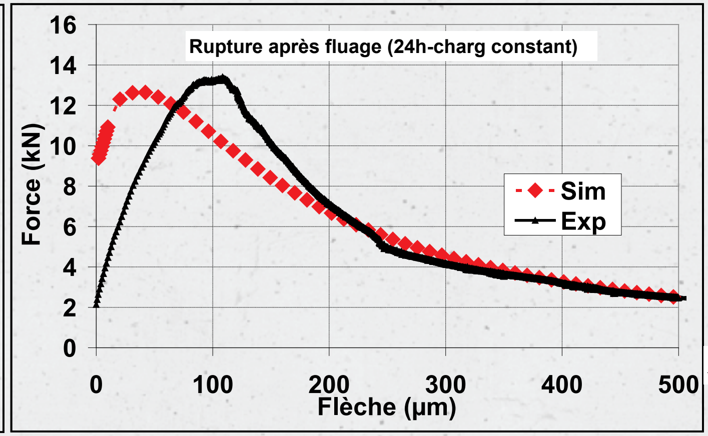




ANALYSIS OF THE CREEP OF CONCRETE

Multiscale modelling of the creep tests

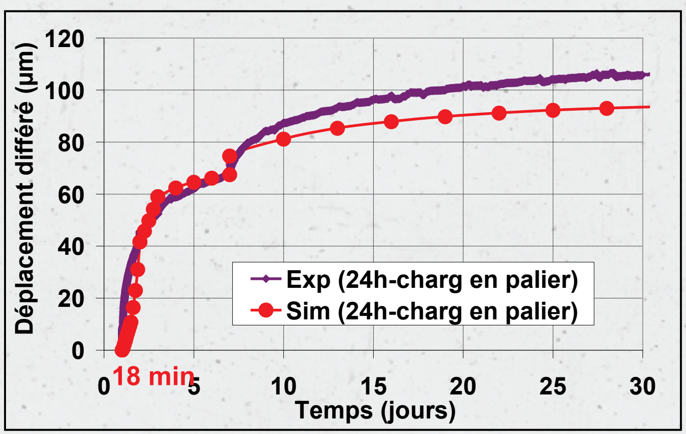


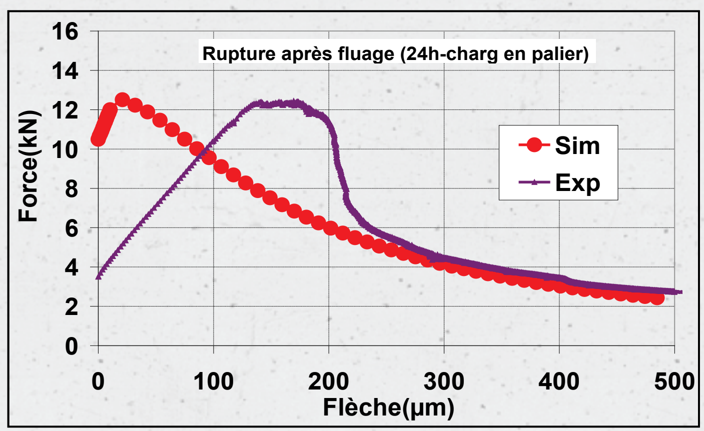


$$\frac{\left(\frac{\Delta F_{28cs}}{\Delta f_{28cs}}\right)}{\left(\frac{\Delta F_{28ce}}{\Delta f_{28ce}}\right)} = \frac{\left(\frac{48E_{28cs}I}{l}\right)}{\left(\frac{48E_{28ce}I}{l}\right)} = \frac{E_{28cs}}{E_{28ce}} = \frac{0.2}{0.23} = 0.87$$

$$E_{28cs} = 0.87E_{28ce} = (1-d_{28cs})E_{28ce}$$

$d_{28cs}=0.13$





$$\frac{\Delta F_{28ps}}{\Delta f_{28ps}} = 0.15 \xrightarrow{E_{28ce}} d_{28ps} = 0.35$$

$$\frac{\Delta F_{28pe}}{\Delta f_{28pe}} = 0.08 \xrightarrow{E_{28ce}} d_{28pe} = 0.65$$

ANALYSIS OF THE CREEP OF CONCRETE

Multiscale modelling of the creep tests

How to explain this difference ?

- Assumption 1: Damage is underestimated by the model.

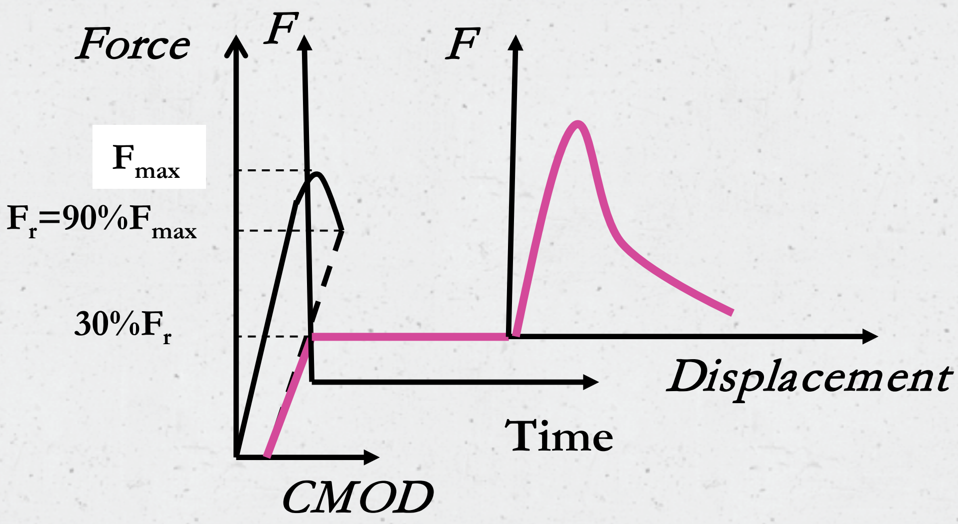
- Assumption 2: There is a damage created by the loading in the experiments that is more accentuated by the increase in the load applied during the bearing load.

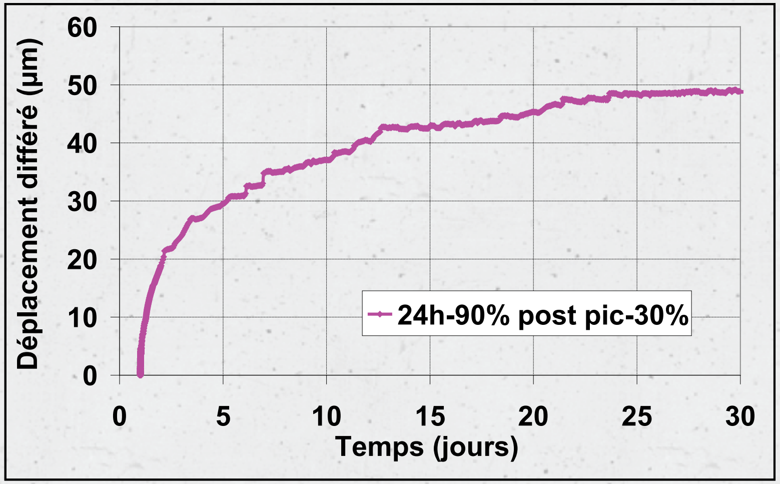
ANALYSIS OF THE CREEP OF CONCRETE

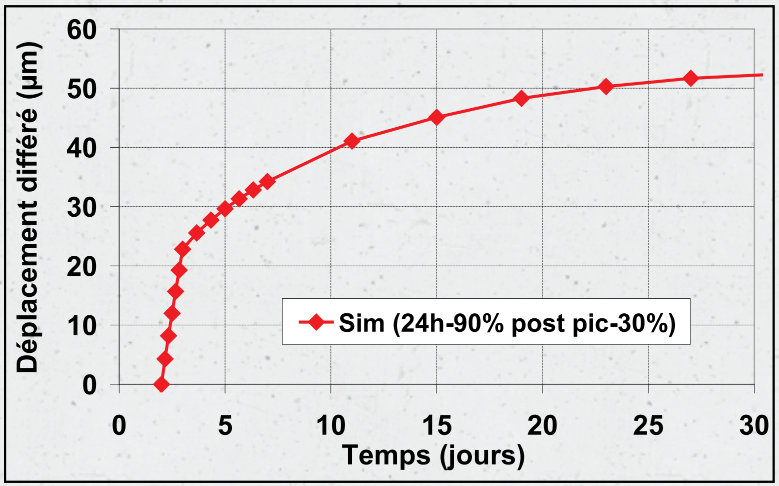
Multiscale modelling of the creep tests

Assumption 1 : underestimation of damage

Creep tests results for pre-cracked beams
(24h-90% post-peak)





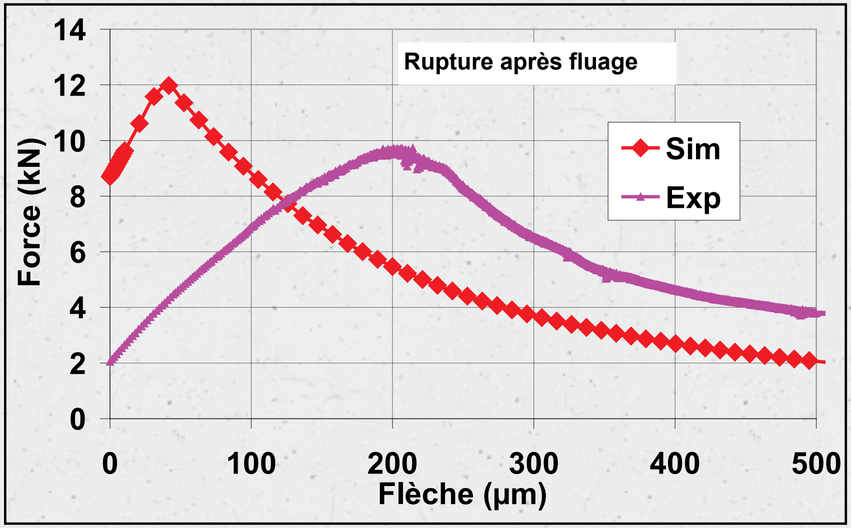


ANALYSIS OF THE CREEP OF CONCRETE

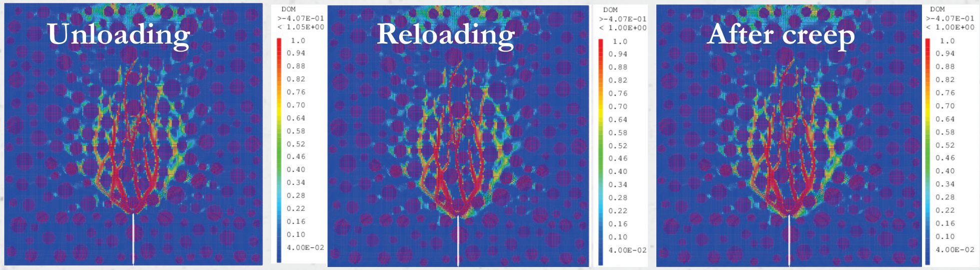
Multiscale modelling of the creep tests

Assumption 1 : underestimation of damage

Creep tests results for pre-cracked beams (24h-90% post-peak)



Age de chargement (h)	Etat de la poutre	Rigidité structurelle (kN/m)	d
24	Pré-endommagée (simulation)	$9\ 10^4$	0.61
	Pré-endommagée (expérience)	$6\ 10^4$	0.74

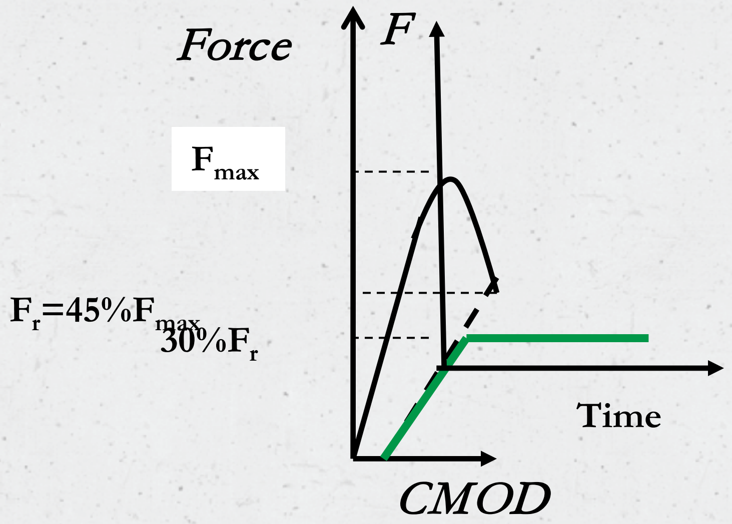


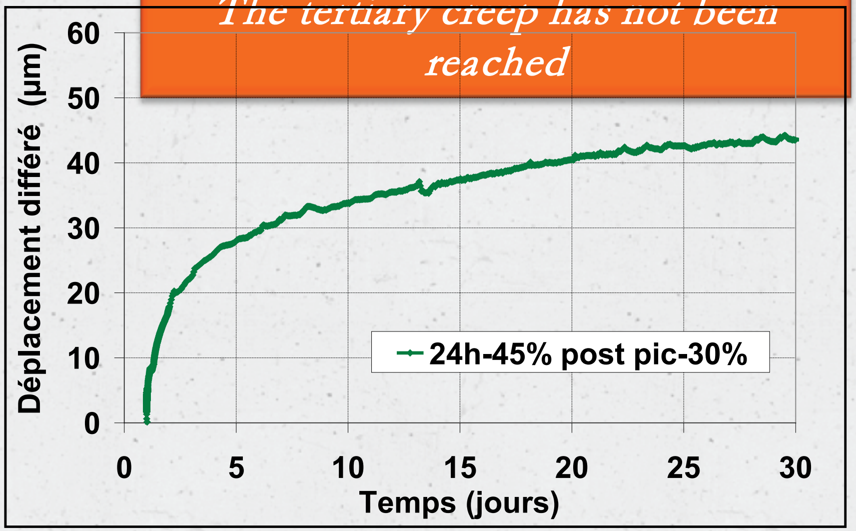
ANALYSIS OF THE CREEP OF CONCRETE

Multiscale modelling of the creep tests

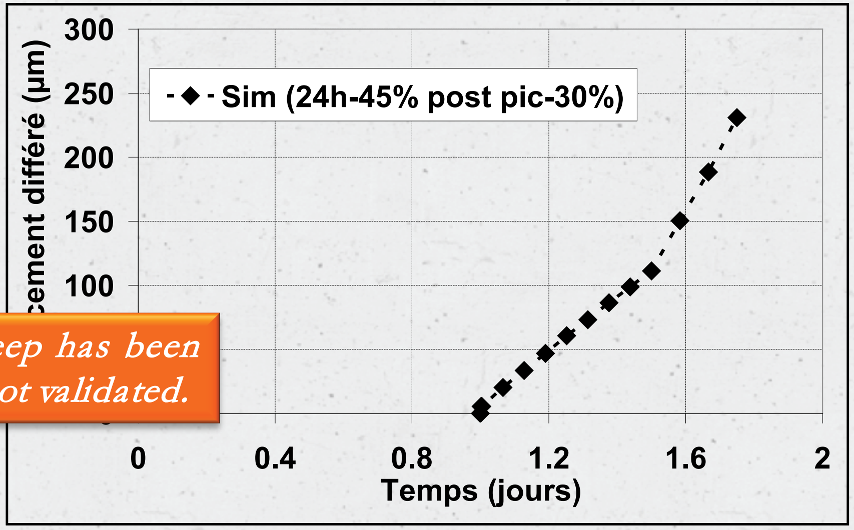
Assumption 1 : underestimation of damage

Creep tests results for pre-cracked beams (24h-45% post-peak)





The tertiary creep has not been reached



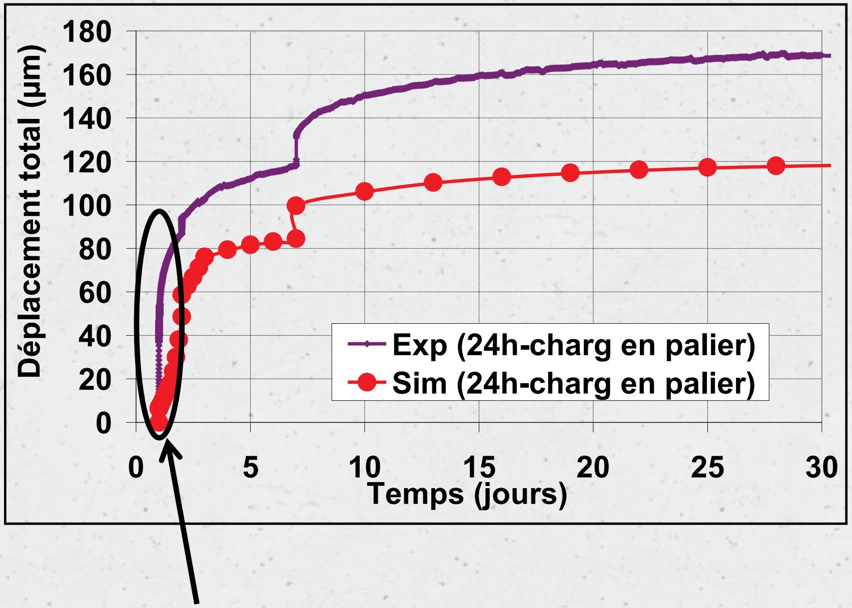
In the simulation the tertiary creep has been reached. So the assumption 2 is not validated.

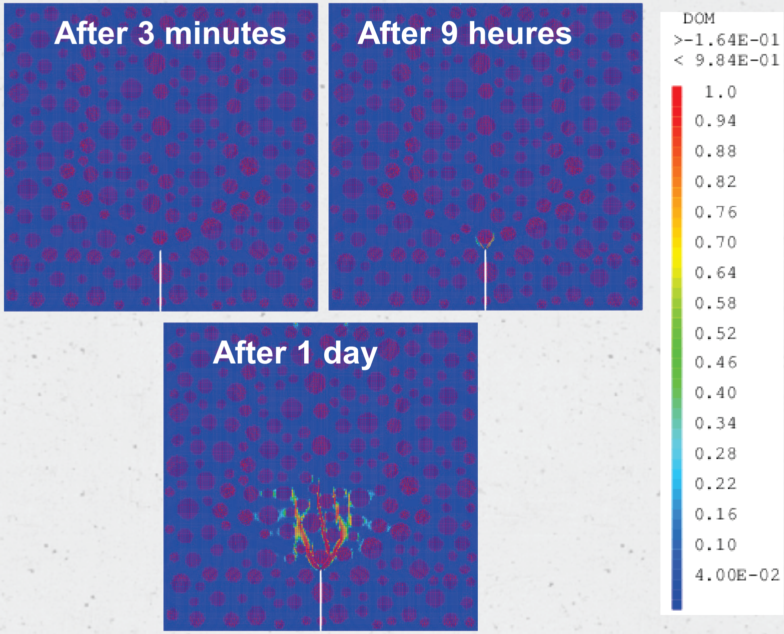
ANALYSIS OF THE CREEP OF CONCRETE

Multiscale modelling of the creep tests

Assumption 2 : damage due to loading to reach the creep force

Comparison of the initial loading between simulations and experiments

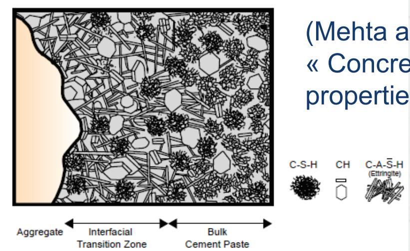




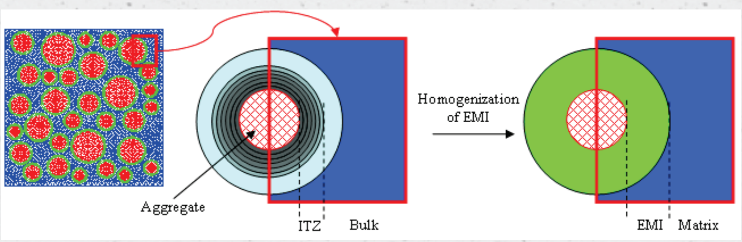
The elastic part in the experimental measurement is more important than that of the simulation

CONCLUSION AND PERSPECTIVES

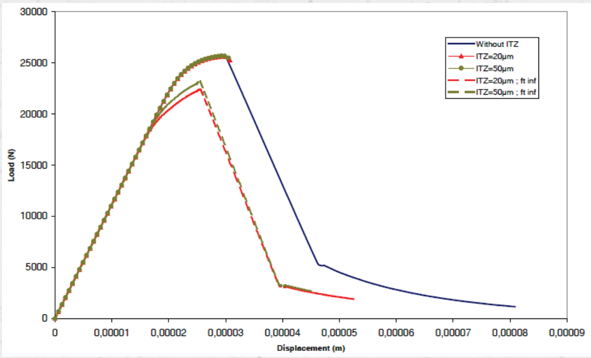
- The multiscale model will be improved by introducing the ITZ



(Mehta and Monteiro, « Concrete: microstructure, properties and materials »)



Grondin, Matallah, Cement Concrete Res, 2014



- The experimental method for creep at early ages will be improved by modifying the loading method

- The damage model will be modified in order to be more significant at microscale

TU 1404
COST ACTION

Back to the list of presentations

MACROSCOPIC MODEL FOR FE ANALYSIS OF CONCRETE EARLY AGE – MULTI-PHASE, POROMECHANICAL APPROACH

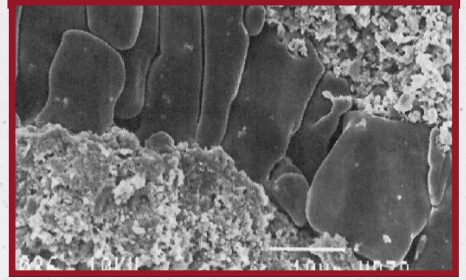
Dariusz Gawin – Łódź University of Technology, Poland
Francesco Pesavento – University of Padova, Italy
Bernhard A. Schrefler – University of Padova, Italy
Giuseppe Sciume - Università del Salento, Italy (prev. University of Padova, Italy)
Mateusz Wyrzykowski – EMPA, Zurich, Switzerland (prev. Łódź TU, Poland)

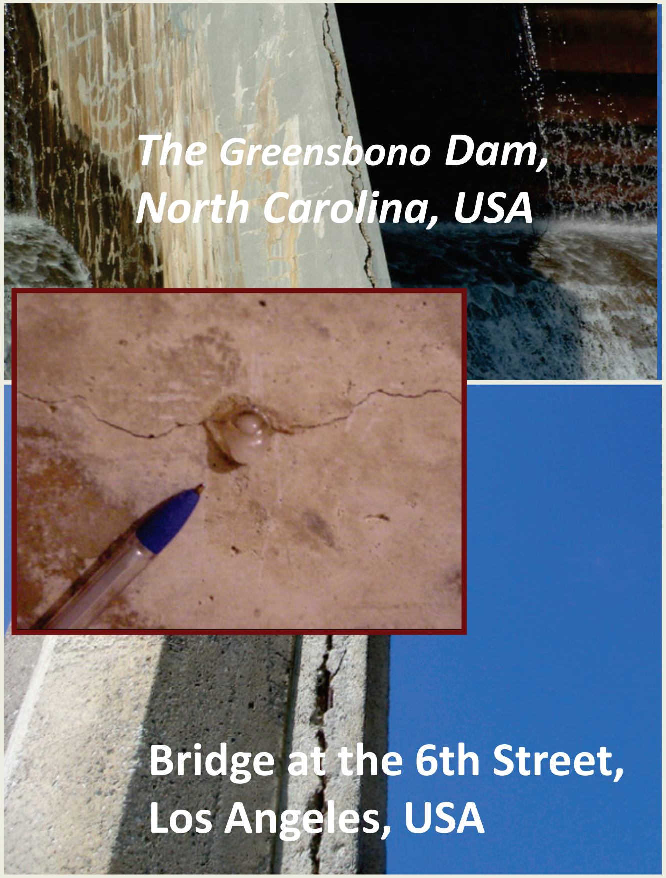
Outline

- ✓ Introduction
- ✓ General approach to modeling concrete
- ✓ Mathematical model of concrete at early ages
- ✓ Numerical solution and validation of the model
- ✓ Examples of application
- ✓ Final remarks

Introduction: motivation

Deterioration of cement based materials: hygral / thermal cracking, Ca leaching, freezing / thawing, salt crystalization, ASR, DER





Introduction: model development

- HTM model of building materials: [Gawin & Schrefler – 1995, 1996]
- CHTM model of concrete at high temperature: [Gawin et al. – 1999],

  [Gawin, Pesavento, Schrefler – 2002, 2003, 2004, 2006, 2011]
- CHTM model of concrete at early ages:

  [Gawin, Pesavento, Schrefler – 2006a,b, 2007], [Wyrzykowski et al. – 2011, 2012]
- CHTM model of concrete exposed to salt deterioration:

  [Koniorczyk, Gawin – 2008, 2011, 2012]

fundamentowej nowego bloku energetycznego Elektrowni Bełchatów, Budownictwo Technologie Architektura, 2007, Vol. 40 (4), s. 56-61.

Introduction: model development

- CTHM model of concrete exposed to calcium leaching:

  [Gawin, Pesavento, Schrefler – 2008a,b, 2009]

- CHTM model of concrete exposed to ASR:

  [Pesavento et al. – 2012]

- HTM model of fully sat. concrete exposed to freezing / thawing:

  [Koniorczyk, Gawin, Schrefler – 2015],

- HTM model of partialy sat. concrete exposed to freezing / thawing::

  [Gawin, Pesavento, Schrefler – in prep.]

Introduction: model development

- Cooperation of University of Padova & Łódź University of Technology
- Italian team:

  B.A. Schrefler, F. Pesavento, G. Sciume, L. Simoni, C. Majorana

- Polish team:

  D. Gawin, M. Koniorczyk, M. Wyrzykowski, A. Witek, W. Grymin

Approach:
considering chemo- hygro- thermo- mechanical couplings

Phenomena	Hygral	Thermal	Chemical	Mechanical
Hygral	- Capillary water flow - Adsorbed water flow - Vapor flow - Effect of RH on the transport properties	- Heat convection - Latent heat of phase change - Effect of RH on the thermal properties	- Effect of RH on the reaction kinetics	- Shrinkage - Creep
Thermal	- Effect of temperature on the moisture transport properties - Thermo-diffusion of water & vapor	- Heat conduction - Effect of temperature on the thermal properties	- Arhenius law (activation energy)	- Free thermal expansion - Effect of temperature on the mat. strength properties
Chemical	- Osmosis -Effect of salts on the sorption isotherm	- Latent heat of chemical reaction - Effect of the reaction products on the thermal properties	- Kinetics law	- Effect of RH on the chemical strains
Mechanical	- Effect of cracks on the permeability - Effect of cracks on the sorption isotherm	- Effect of cracks on the thermal conductivity & convective heat transport	- Effect of material cracking on the reaction kinetics (e.g. crystallization)	- Effect of mechanical degradation (cracking) on the mat. strength

Approach: components and transport mechanisms

Capillary water (free water):

- ✓ advective flow *(water pressure gradient)*

Physically adsorbed water:

- ✓ diffusive flow *(water concentration gradient)*

Chemically bound water:

- ✓ no transport

Water vapour:

- ✓ advective flow *(gas pressure gradient)*
- ✓ diffusive flow *(water vapour concentration gradient)*

Dry air:

- ✓ advective flow *(gas pressure gradient)*
- ✓ diffusive flow *(dry air concentration gradient)*

Approach: components and transport mechanisms

Capillary water (free water):

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- ✓ diffusive flow *(water vapour concentration gradient)*

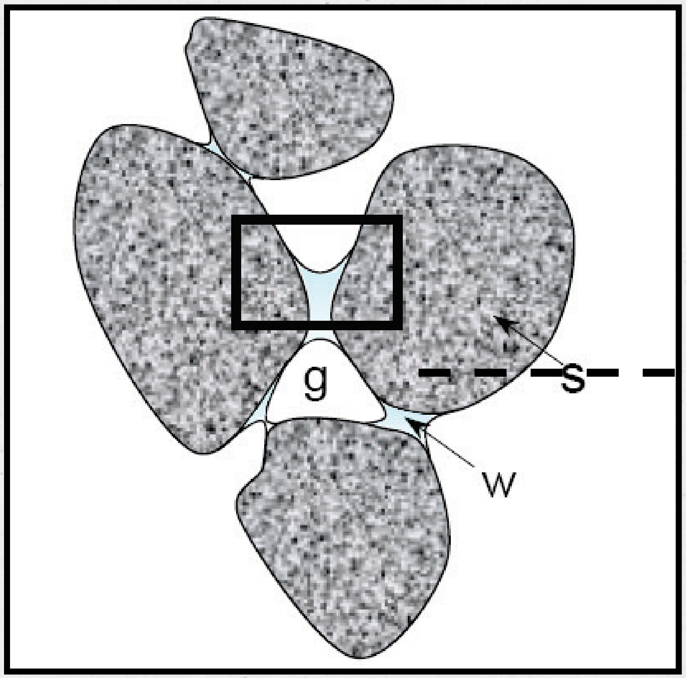
Dry air:

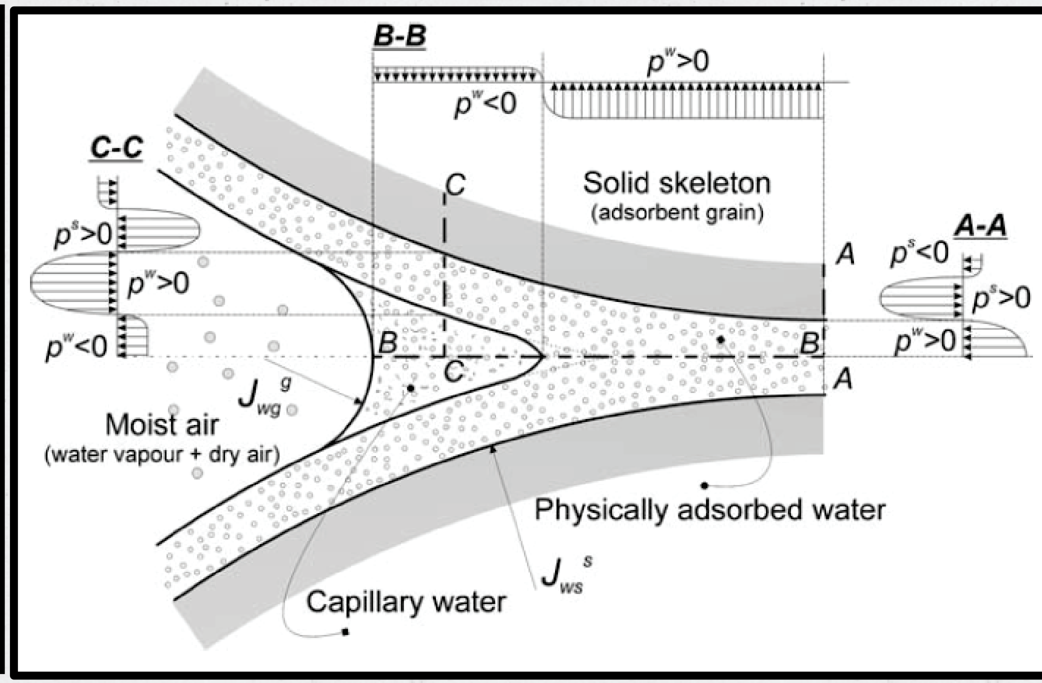
- ✓ advective flow *(gas pressure gradient)*
- ✓ diffusive flow *(dry air concentration gradient)*

Approach: phase changes and reactions

- ***Evaporation:*** capillary water + energy ⇒ water vapour
- ***Condensation:*** water vapour ⇒ capillary water + energy
- ***Desorption:*** phys. adsorbed water + energy ⇒ water vapour
- ***Adsorption:*** water vapour ⇒ phys. adsorbed water + energy
- ***Dehydration:*** solid matrix + energy ⇒ bound water water
- ***Hydration:*** chemically bound water ⇒ solid matrix + energy

Approach: multiphase system





The pores are filled by two phases:
-Liquid phase
-Gas phase (vapour + dry air)

Dalton law $P_g = P_{da} + P_v$

Local equilibrium

$$P_c = P_g - P_w$$

Approach:

Evolution of reactions / processes in a rate form

Free water → Chemically bound water

[Ulm & Coussy, 1996]

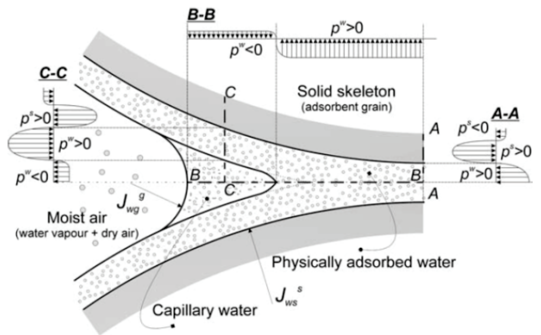
$$\frac{d\Gamma_{hydr}}{dt} = \tilde{A}_{\Gamma}\left(\Gamma_{hydr}\right)\exp\left(-\frac{E_a}{RT}\right)$$

where $$\Gamma_{hydr} = \frac{\chi}{\chi_{\infty}} = \frac{m_{hydr}}{m_{hydr\infty}}$$

$\tilde{A}_{\Gamma}(\Gamma_{hydr})$ - hydration degree-related, normalized affinity, χ - hydration extent,

E_a – hydration activation energy, R – universal gas constant, t – time.

Approach: Micro → Macro averaging



LOCAL FORMULATION
(MICRO-SCALE, DETAIL OF THE REV)

Upscaling

Thermodynamically Constrained Averaging Theory *(Gray & Miller, 2005)*

System of governing equations:

- Mass conservation equations of the phases;
- Linear momentum balance equations;
- Mass balance equations of the species.

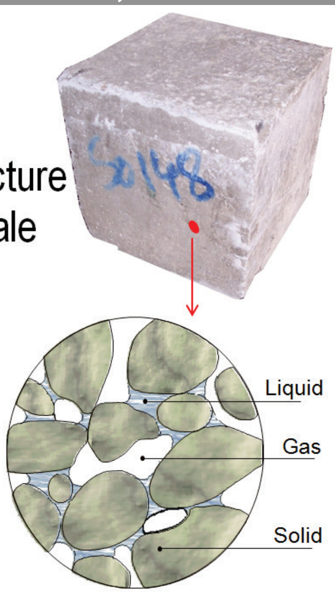
MACROSCOPIC FORMULATION

Closure relationships

NUMERICAL SOLUTION

FEM (in space)
FDM (in the time domain)

Structure scale



REV

i) The Representative Elementary Volume (REV) at microscopic level must be large enough so that averages of properties are independent of the sample size.

ii) The REV must contain all phases.

iii) REV represents a point in the macroscopic description: REV must be small enough so that partial derivatives at macroscopic level make sense

Mathematical Model: evolution equations

EVOLUTION EQUATIONS:

- ✓ Evolution equation for hydration/dehydration
- ✓ Evolution equation for material damage (cracking)
- ✓ Evolution equation for termo-chemical damage

INTERNAL VARIABLES:

- ✓ Hydration/Dehydration degree – Γ_{hydr}
- ✓ Mechanical damage degree – d
- ✓ Thermo-chemical damage degree - V

Introduction: modelling of concrete at early ages (& beyond)

Creep in concrete

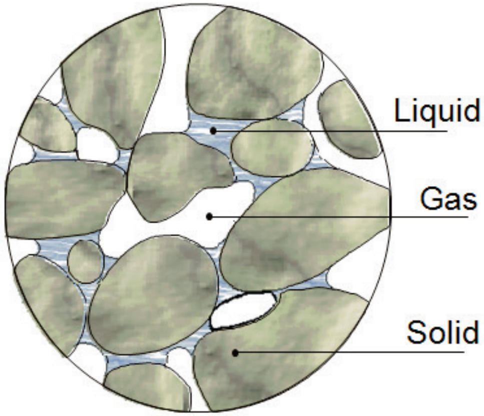
- ✓ Bazant, Wittmann (eds)- 1982
- ✓ Bazant et al. – 1972 - 2002
- ✓ Harmathy - 1969
- ✓ Bazant, Chern – 1978 - 1987
- ✓ Hansen - 1987
- ✓ Bazant, Prasannan - 1989
- ✓ De Schutter, Taerwe - 1997
- ✓ Sercombe, Hellmich, Ulm, Mang - 2000

Hydration of cement

- ✓ Jensen - 1995
- ✓ van Breugel - 1995
- ✓ De Schutter, Taerwe - 1995
- ✓ Singh et al. – 1995
- ✓ Ulm, Coussy -1996
- ✓ Bentz et al. – 1998, 1999
- ✓ Sha et al. - 1999

Mathematical Model: the multiphase system

Concrete is treated as a **porous solid** and porosity is denoted by ε, so that the volume fraction occupied by the solid skeleton is $\varepsilon^s = 1 - \varepsilon$. The rest of the volume is occupied by the liquid water (ε^l); and the gaseous phase (ε^g).

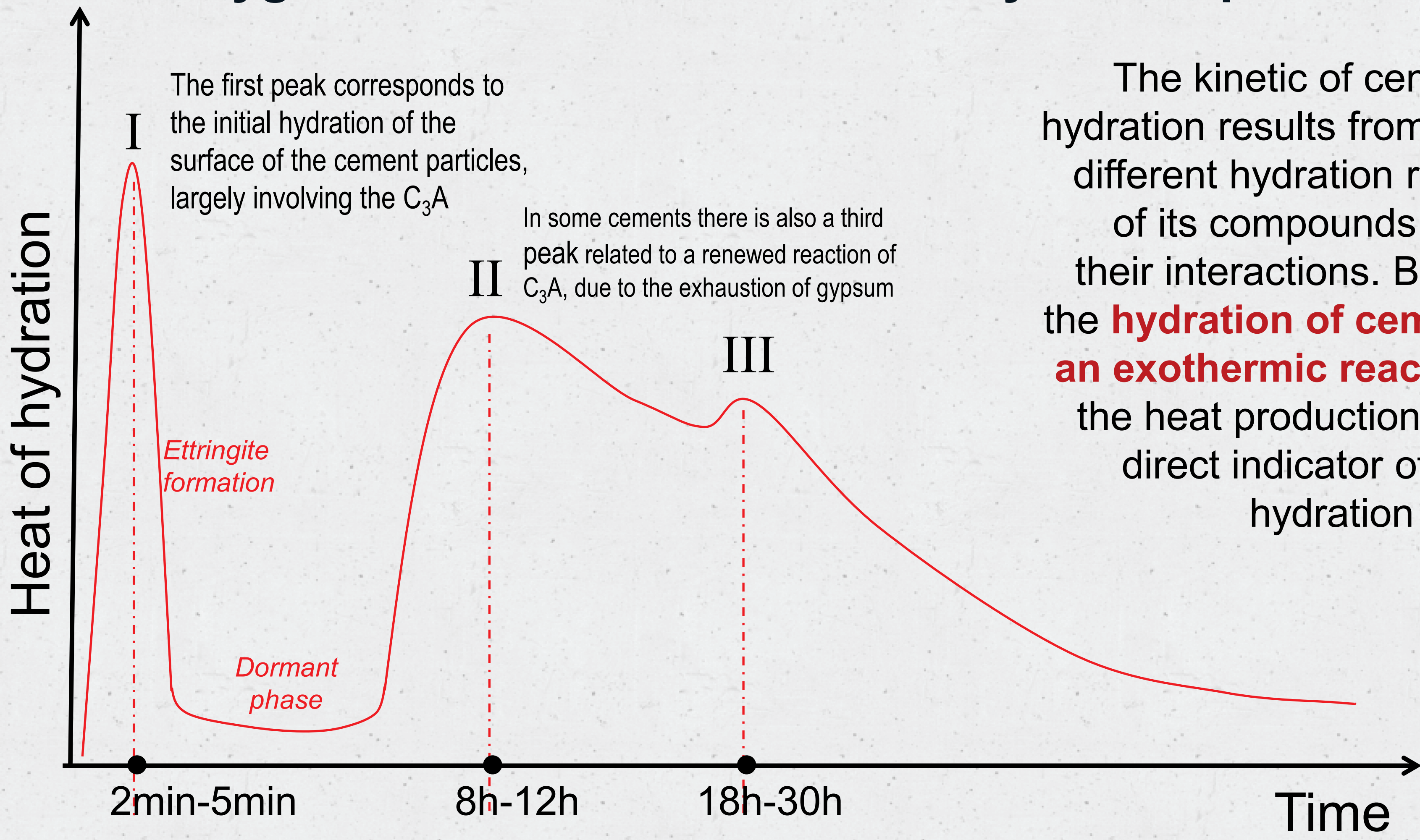


1 Solid phase *s*:
- Anhydrous cement: Cs
- Aggregates: As
- Hydrates: Hs

1 liquid phases *l*:
- Liquid water

1 Gaseous phase *g*:
- Water vapour: Wg
- Dry air: Ag

Chemo - hygrothermal interactions : the hydration process



The kinetic of cement hydration results from the different hydration rates of its compounds and their interactions. Being the **hydration of cement an exothermic reaction** the heat production is a direct indicator of the hydration rate

Chemo - hygrothermal interactions: hydration evolution

Evolution of the hydration degree

[Gawin, Pesavento, Schrefler, IJNME 2006 part 1 and part 2]

$$x \cdot (\text{unhydrated cement}) + w \cdot H_2O \rightarrow z \cdot (\text{hydrated cement})$$

$$A_{\Gamma} \equiv x \cdot \mu_{unhydr} + w \cdot \mu_{water} - z \cdot \mu_{hydr}$$

$$d\chi = \frac{dN_{unhydr}}{-x} = \frac{dN_{water}}{-w} = \frac{dN_{hydr}}{z}$$

where

$A_{\Gamma}(\Gamma_{hydr})$ - hydration degree-related chemical affinity, χ - hydration extend,

μ – chemical potential, N – mole number, x, w, z - stoichiometric coefficients.

Chemo - hygrothermal interactions: hydration evolution

Evolution of the hydration degree

[Gawin, Pesavento, Schrefler, IJNME 2006 part 1 and part 2]

$$\frac{d\Gamma_{hydr}}{dt} = \tilde{A}_{\Gamma}\left(\Gamma_{hydr}\right)\beta_{\varphi}\left(\Gamma_{hydr},\varphi\right)\exp\left(-\frac{E_a}{RT}\right)$$

Effect of relative humidity

where

$$\Gamma_{hydr} = \frac{\chi}{\chi_{\infty}} = \frac{m_{hydr}}{m_{hydr\infty}}$$

$\tilde{A}_{\Gamma}(\Gamma_{hydr})$ - hydration degree-related, normalized affinity, χ - hydration extent,

E_a – hydration activation energy, R – universal gas constant, t – time.

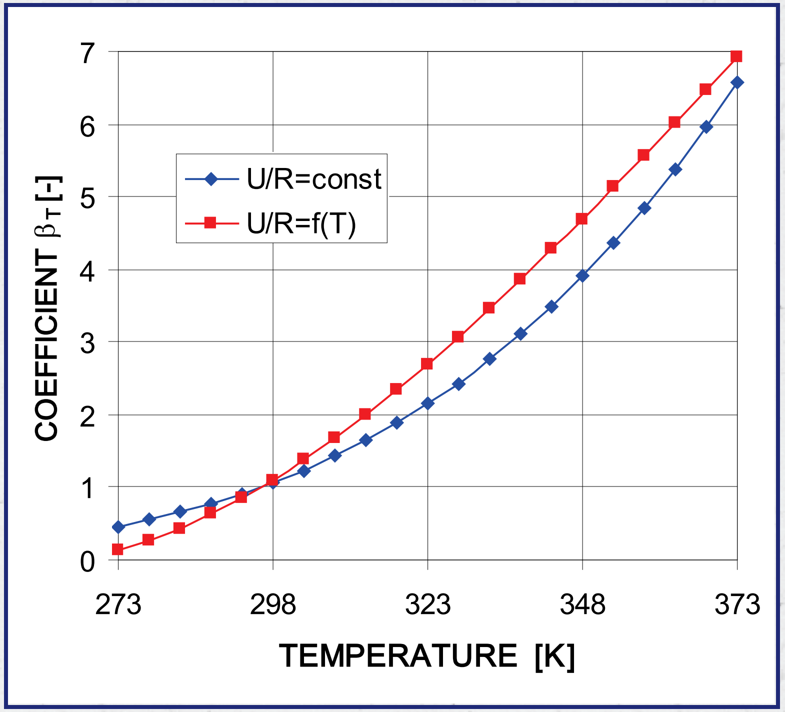
$$\tilde{A}_{\Gamma}(\Gamma_{hydr}) = A_1\left(\frac{A_2}{\kappa_{\infty}} + \kappa_{\infty}\Gamma_{hydr}\right)(1-\Gamma_{hydr})\exp(-\bar{\eta}\,\Gamma_{hydr})$$

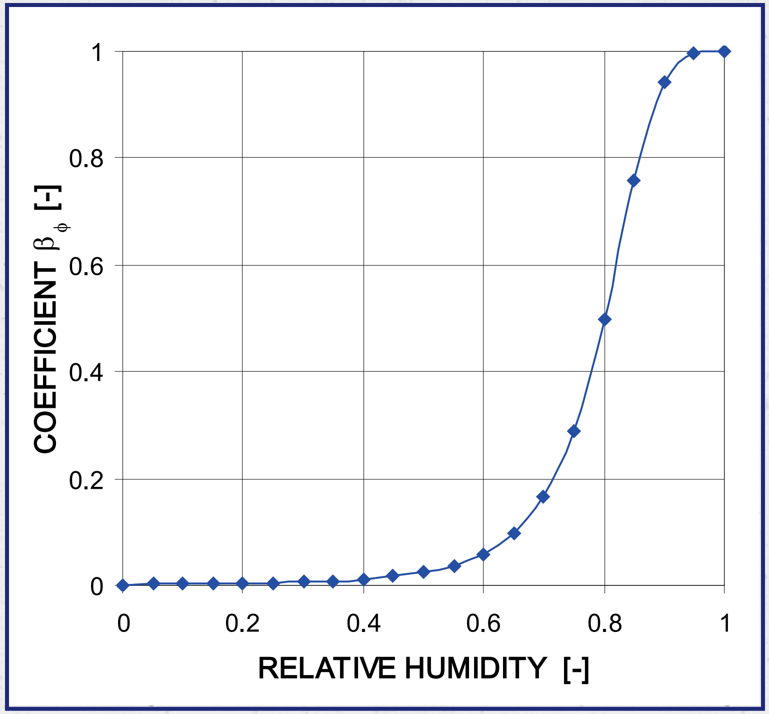
➢ *from: [Cervera, Olivier, Prato, 1999]*

Chemo - hygrothermal interactions
Evolution of the hydration process

Influence of the temperature and relative humidity

[Bazant, 1988]

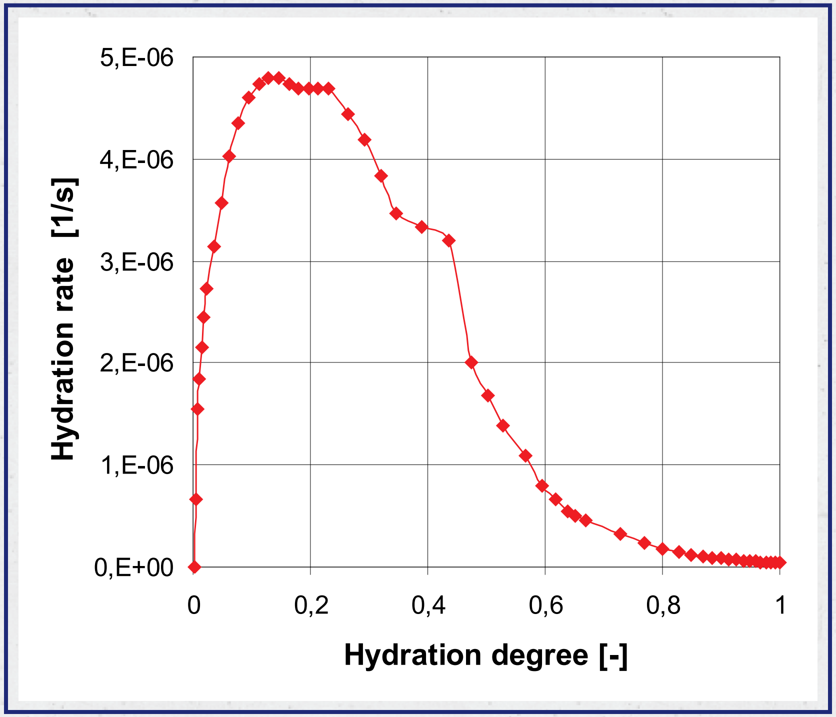




Chemo - hygrothermal interactions

Evolution of the hydration proces

Influence of the hydration rate on the heat- & mass- sources



$$\frac{\partial Q_{hydr}}{\partial t} = \frac{\partial \Gamma_{hydr}}{\partial t} Q_{hydr\infty} = \frac{\partial m_{hydr}}{\partial t} \Delta H_{hydr}$$

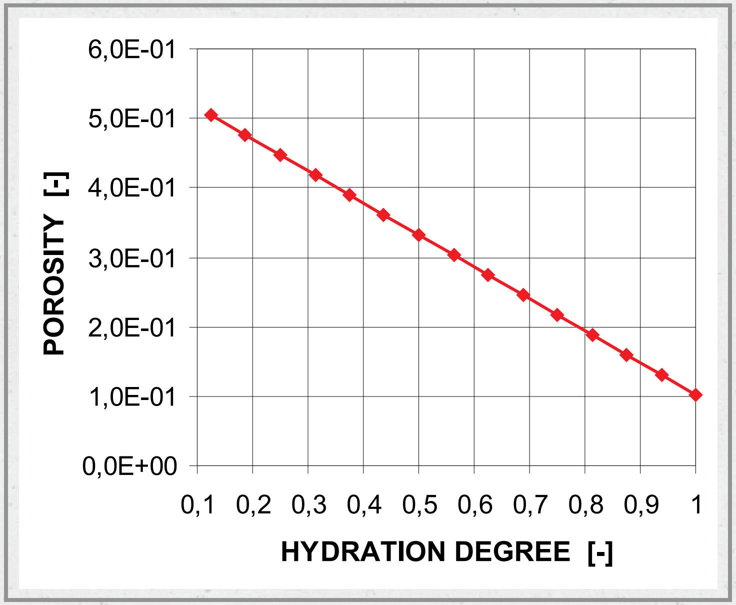
$$\dot{m}_{hydr} = \frac{\partial m_{hydr}}{\partial t} = \frac{\partial \Gamma_{hydr}}{\partial t} m_{hydr\infty}$$

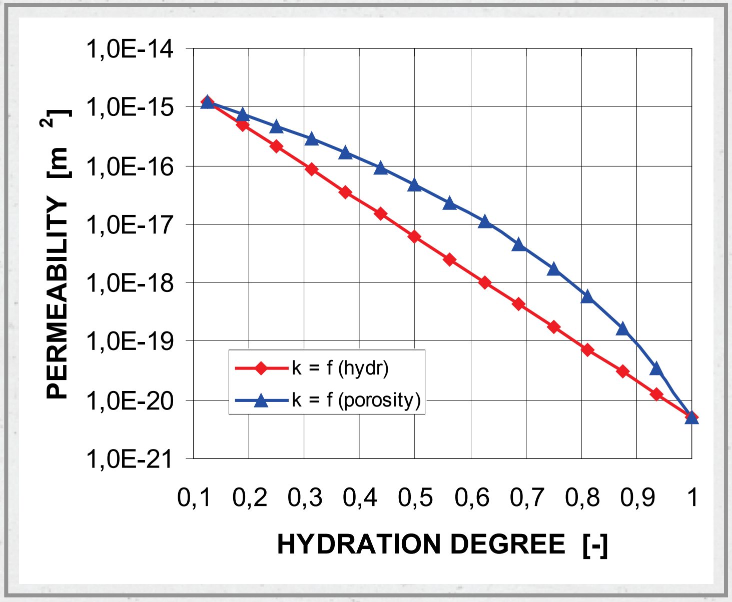
Hydration rate

where:
m_{hydr} – mass of chemically bound water,
Q_{hydr} – heat of hydration

Hygro-structural - chemical interactions
Evolution of the material properties

Evolution of concrete porosity & permeability:





$$n\left(\Gamma_{hydr}\right) = n_\infty + A_n\left(\Gamma_{hydr} - 1\right)$$

$$k\left(n\right) = k_\infty \cdot 10^{A_{kn}\left(n - n_\infty\right)}$$

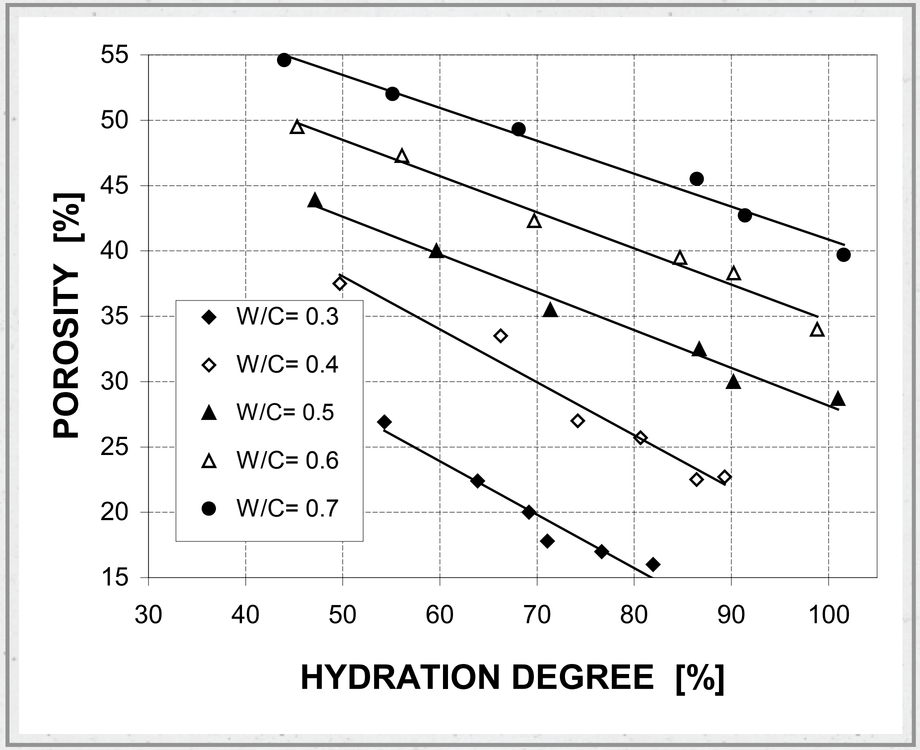
$$k\left(\Gamma_{hydr}\right) = k_\infty \cdot 10^{A_{k\Gamma}\Gamma_{hydr}}$$

[Halamickova, Detwiler, Bentz, Garboczi, 1995]

[Halamickova et al., 1995, Kaviany, 1999]

Hygro-structural - chemical interactions
Evolution of the material properties

Evolution of concrete porosity & permeability:

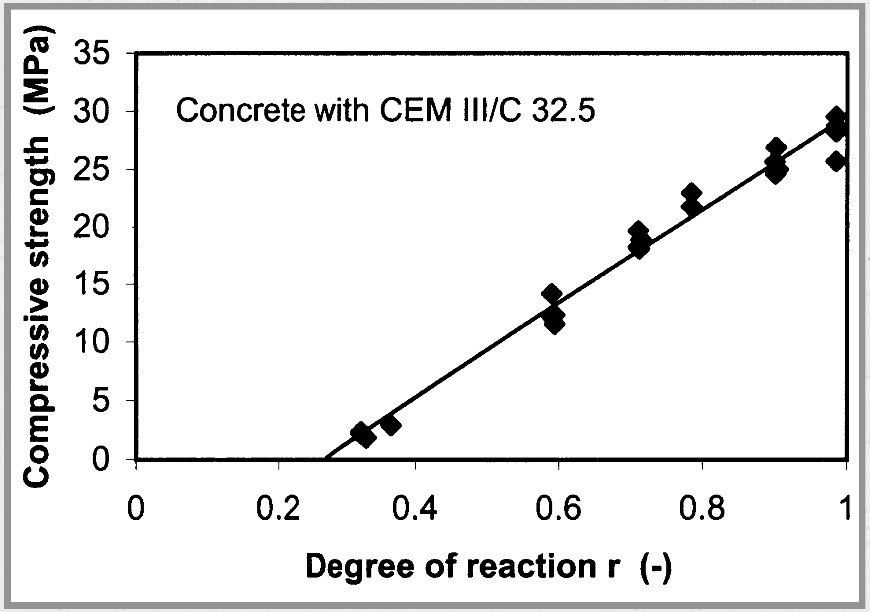


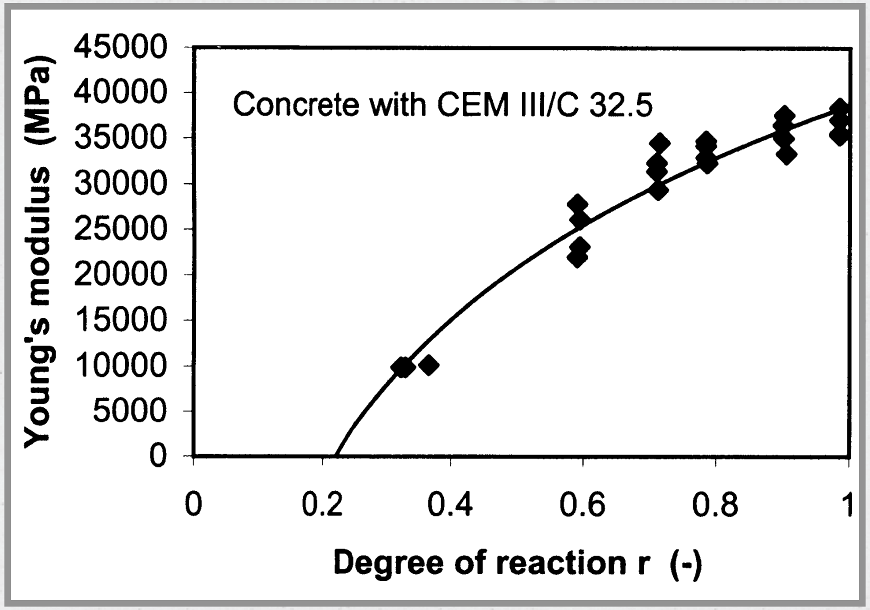
Experimental results from [Cook & Hover, 1999]

Hygro-structural - chemical interactions

Evolution of the material properties

Evolution of concrete strength properties:



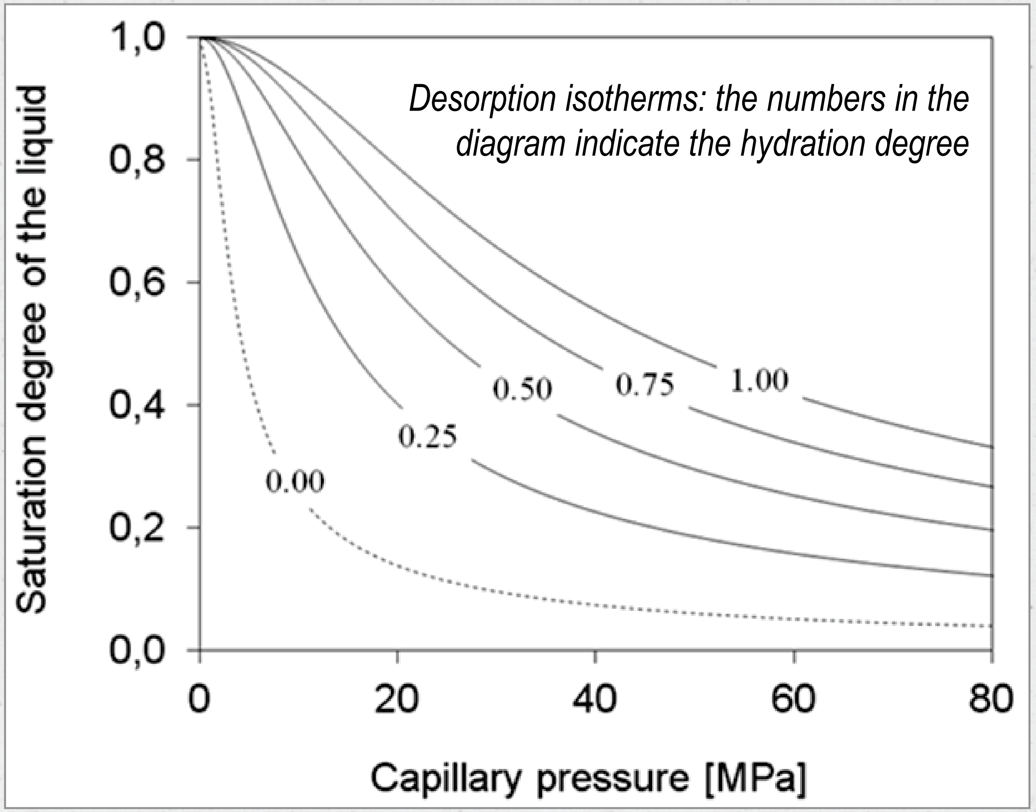


From [De Schutter, 2002]

Mathematical model

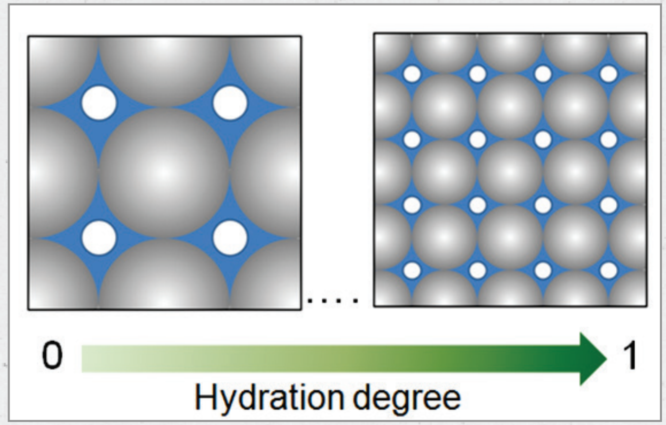
Hydration dependent desorption isotherm

The desorption isotherm is closely linked with the microstructure of the cement paste that shows important changes during hydration (refinement of the porous network).



Van Genuchten modified analytical expression

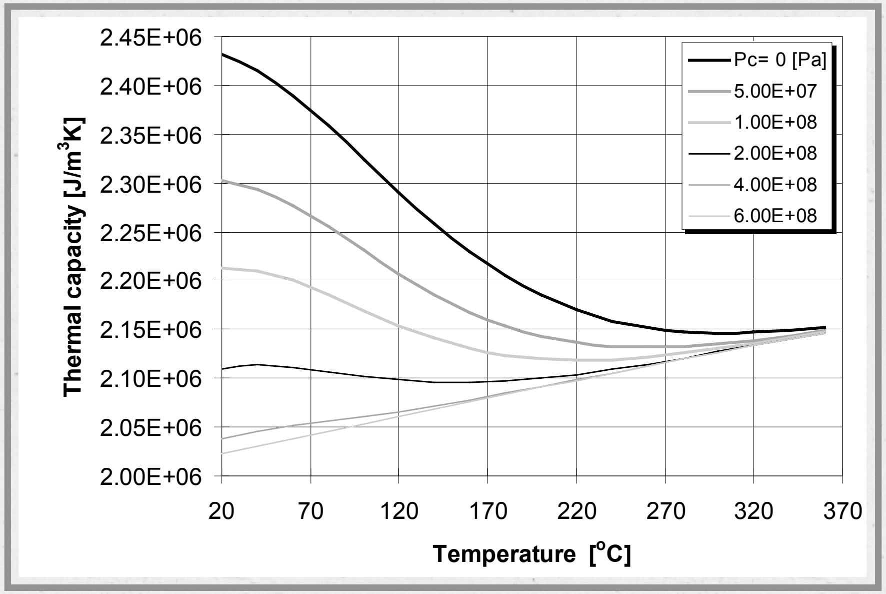
$$S_w = \left\{ 1 + \left[\frac{p_c}{a} \left(\frac{\Gamma + \Gamma_i}{1 + \Gamma_i} \right)^{-c} \right]^{\frac{b}{b-1}} \right\}^{-\frac{1}{b}}$$



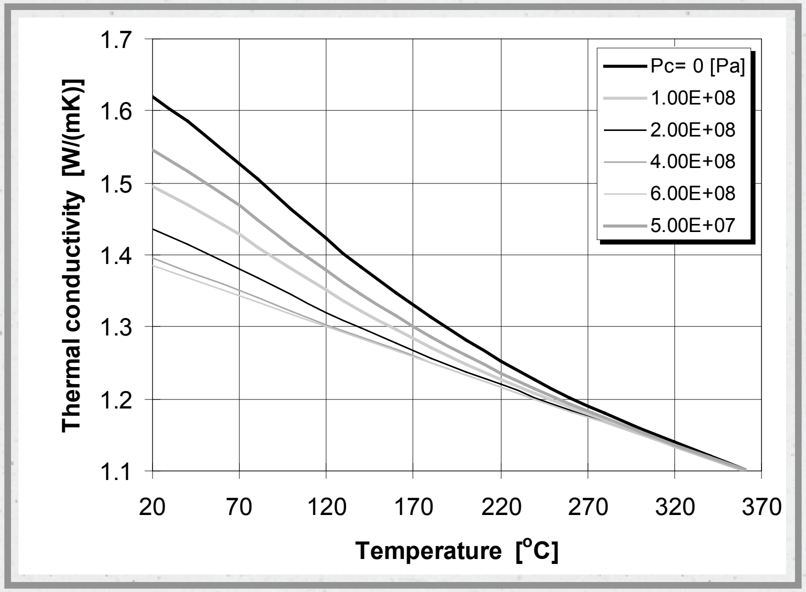
Mathematical model

Constitutive relationships for thermal properties

Thermal capacity



Thermal conductivity



$$\rho C_p = (1-n)\rho^s C_{ps} + n\left[S\rho^w C_{pw} + (1-S)\left(\rho^g C_{pga} + \rho^{gw}\left(C_{pgw} - C_{pga}\right)\right)\right]$$

$$\rho C_{ps} = \rho C_{pso}\left[1 + A_c\left(T - T_o\right)\right]$$

$$\chi_{eff} = \chi_d(T)\left(1 + \frac{4 n \rho^w S}{(1-n)\rho^s}\right)$$

$$\chi_d = \chi_{do}\left[1 + A_\chi\left(T - T_o\right)\right]$$

Mathematical model
Constitutive relationships for concrete at early ages

Heat source equation ⟶

$$\frac{\partial Q_{hydr}}{\partial t} = \frac{\partial \Gamma_{hydr}}{\partial t} Q_{hydr\infty} = \frac{\partial m_{hydr}}{\partial t} \Delta H_{hydr}$$

Mass source equation ⟶

$$\dot{m}_{hydr} = \frac{\partial m_{hydr}}{\partial t} = \frac{\partial \Gamma_{hydr}}{\partial t} m_{hydr\infty}$$

Intrinsic permeability ⟶

$$k\left(\Gamma_{hydr}\right) = k_\infty \cdot 10^{A_{k\Gamma}\Gamma_{hydr}}$$

Porosity ⟶

$$n\left(\Gamma_{hydr}\right) = n_\infty + A_n\left(\Gamma_{hydr} - 1\right)$$

Density ⟶

$$\rho_s\left(T,\Gamma_{hydr}\right) = \rho^s\left(T\right)\left[1 - n\left(\Gamma_{hydr}\right)\right]$$

Thermal conductivity ⟶

$$\lambda_{eff} = \lambda_{dry}\left(T\right)\left[1 + \frac{4n\rho^w S_w}{\left(1-n\right)\rho^s}\right]$$

Saturation degree ⟶

$$S_w = \left[1 + \left(\frac{p^c}{a}\right)^{b/(b-1)}\right]^{-1/b}$$

Chemo- mechanical interactions

Strain components

In general, a total strain of maturing concrete, ε_{tot}, can be split into :

1. *free thermal strain*
2. *thermo-chemical strain*
3. *creep strain*
4. *mechanical strain (caused by mechanical load and shrinkage)*

Strain decomposition

$$d\boldsymbol{\varepsilon}_{mech} = d\boldsymbol{\varepsilon}_{tot} - d\boldsymbol{\varepsilon}_{c} - d\boldsymbol{\varepsilon}_{th} - d\boldsymbol{\varepsilon}_{ch}$$

Shrinkage strain

$$d\boldsymbol{\varepsilon}_{sh} = -\frac{\alpha}{3K_T}\left(d\chi^{ws} p^c + \chi^{ws} dp^c \right)\mathbf{I}$$

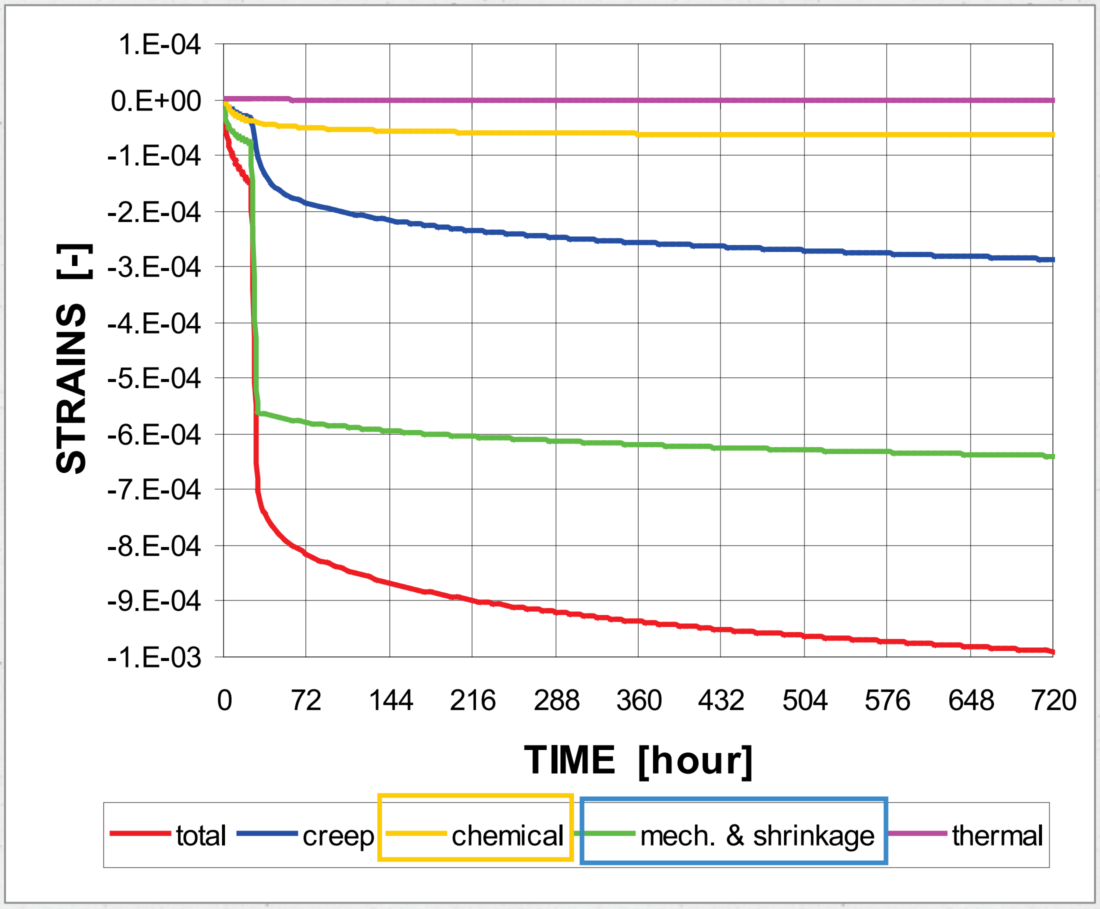
Free thermal strain strain

$$d\boldsymbol{\varepsilon}_t = \beta_s \, dT \, \mathbf{I}$$

Thermo-chemical strain

$$d\boldsymbol{\varepsilon}_{ch} = \beta_{ch} \, d\Gamma_{hydr} \, \mathbf{I}$$

Chemo- mechanical interactions
Strain components



$$d\boldsymbol{\varepsilon}_{chem} = \beta_{chem}\left(\Gamma_{hydr}\right) d\Gamma_{hydr}$$

ε_{chem} - chemical strain
(irreversible)

details:

- *[Gawin, Pesavento, Schrefler, IJNME 2006]*

Caused by:
mechanical load and shrinkage

Hygro-mechanical interactions

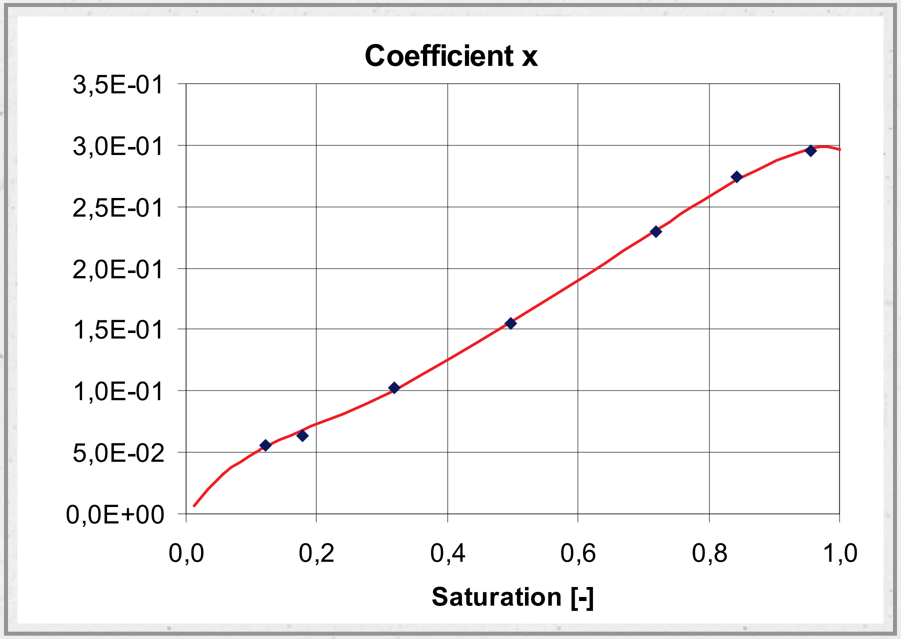
Shrinkage of concrete

Effective stress principle:

$$\boldsymbol{\sigma}_e^s = \boldsymbol{\sigma}^s + \alpha \mathbf{I} p^s$$

$$p^s = p^g - \chi_s^{ws} p^c$$

➢[Gray & Schrefler, 2001]



where x_s^{ws} is the solid surface fraction in contact with the wetting film,

I - unit, second order tensor, α - Biot's coefficient,

p^s - pressure in the solid phase

Mathematical model

Constitutive law for creep strain

Solidification theory for basic creep

$$d\mathbf{t}^{ef} = \mathbf{D}\left(d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}_c - d\boldsymbol{\varepsilon}_{th} - d\boldsymbol{\varepsilon}_{ch}\right) + d\mathbf{D}\left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_c - \boldsymbol{\varepsilon}_{th} - \boldsymbol{\varepsilon}_{ch}\right)$$

$$d\boldsymbol{\varepsilon}_c = d\boldsymbol{\varepsilon}_v + d\boldsymbol{\varepsilon}_f$$

where

$$\dot{\varepsilon}_v(t) = \frac{F\left[\mathbf{t}^{ef}(t)\right]}{\Gamma_{hydr}(t)}\dot{\gamma}(t) \qquad \dot{\varepsilon}_f(t) = \frac{F\left[\mathbf{t}^{ef}(t)\right]\mathbf{t}^{ef}(t)}{\eta(t)}$$

Hydration degree

Effective stress

- $\dot{\varepsilon}_c$ - creep strains (as sum of viscoelastic and viscous (flow) term);
- $\dot{\varepsilon}_v$ - viscoelastic term;
- $\dot{\varepsilon}_f$ - flow term;
- γ - viscoelastic microstrain;
- η - apparent macroscopic viscosity

Details:

- *[Bazant Z.P. Prasannan S., J.Eng.Mech., 1989]*
- *[Gawin, Pesavento, B.A. Schrefler J.N.M.E, 2006]*

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Mathematical model

Constitutive law for creep strain

Log-Power law:

$$\Phi\left(t-t'\right)=q_2\ln\left[1+\left(\frac{\xi}{\lambda_0}\right)^n\right]$$

$$\frac{1}{v\left(t\right)}=\frac{1}{\Gamma_{hydr}\left(t\right)}$$

$$\frac{1}{\eta}=cpS^{p-1}$$

Microprestress theory

where

- $\Phi\left(t-t'\right)$ - compliance function
- q_2 - parameter from B3 model
- S - microprestress ;
- p,c - positive constants;
- $v(t)$ - volume fraction of the solified matter;
- λ_0 - constant usually equal to 1;
- α,m - constants of the material;

Details:

- *[Bazant Z.P. Prasannan S., J.Eng.Mech., 1989]*
- *[D. Gawin, F. Pesavento and B.A. Schrefler J.N.M.E, 2006]*

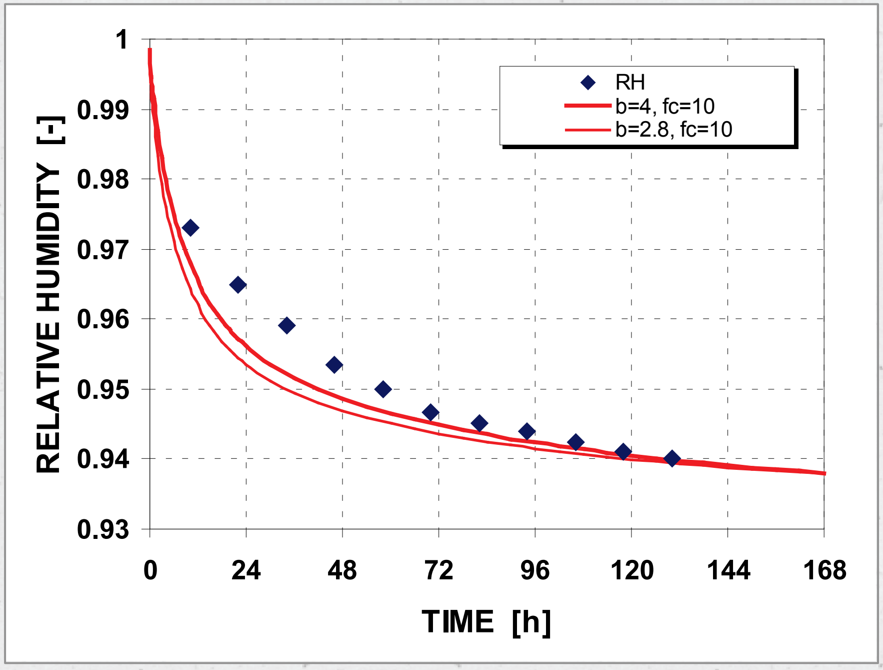
Validation: Autogenous shrinkage in HPC paste

(Lura, Jensen, van Breugel test)

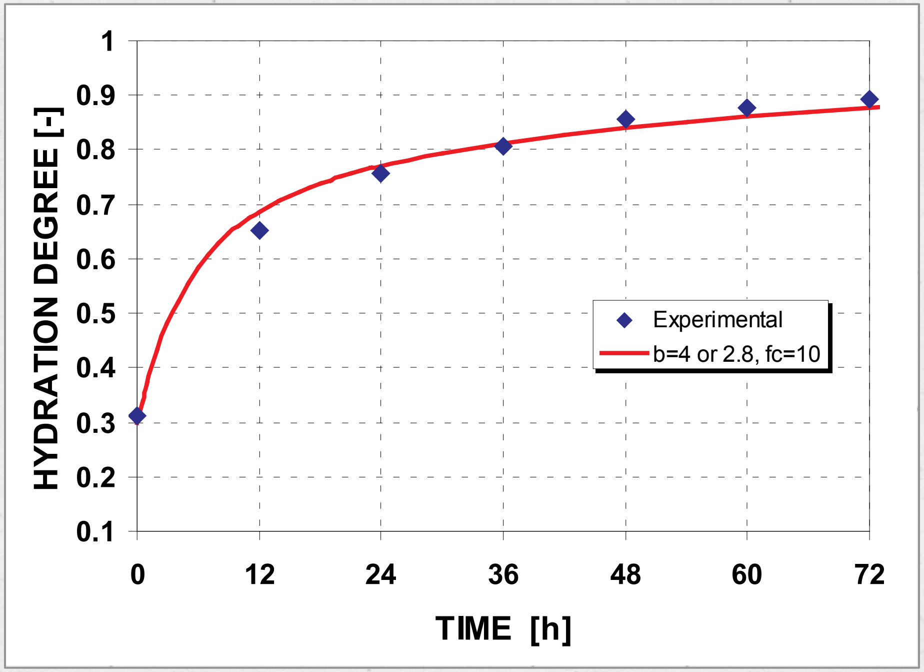
- ✓ Cubic specimen – 50x50x200 mm;
- ✓ Initial conditions:
  T_o= 293.15 K, φ_o= 99.0% RH, Γ_{hydr}=0.1;
- ✓ Boundary conditions:
  - convective heat and mass exchange: sealed (adiabatic)
  - surface mechanical load: unloaded
- ✓ Properties of the cement paste:
  - Elastic modulus measured prior the test (1, 3 and 7 days),
  - curing temperature 20°C

Validation: Autogenous shrinkage in HPC paste

(Lura, Jensen, van Breugel test)



R.H. development in time

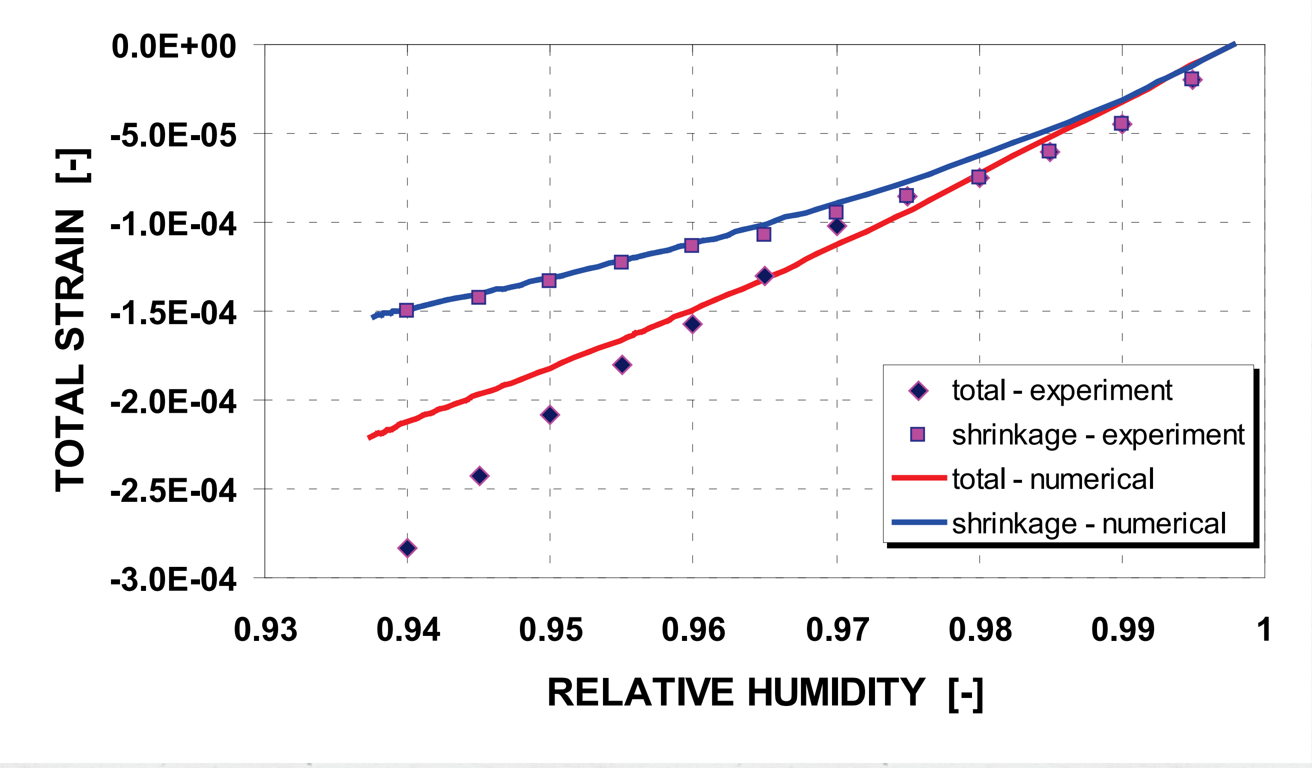


Hydr. Degree development in time

Numerical example

Autogenous shrinkage in HPC paste

(Lura, Jensen, van Breugel test)



Effect of shrinkage – creep coupling

Numerical example: tests of L'Hermite (1965)

- ✓ **Square prism** – 7x7x28 cm; equiv. cylinder ϕ=7.6 cm;
- ✓ Material: concrete C30
  - ☐ - final porosity: 0.122, density: ρ= 1900 kg/m^3,
  - ☐ - intrinsic permeability: k_o= 5·10^{-19} m^2 ,
  - ☐ - Young modulus: E= 38.5 GPa, water/cement ratio w/c=0.45.
- ✓ Initial conditions:

T_o= 293.15 K, φ_o= 99.9% RH, Γ_{hydr}=0.3;

- ✓ Boundary conditions:

Shrinkage ***(from day 1)***

- convective heat and mass exchange: α_c=2W/m^{2}K; β_c=0.0013m/s; RH_{amb}=50%
- surface mechanical load: unloaded or load=4.9, 9.8 and 12.3 MPa at 7, 21, 90 and 180 days

Maturing in water ***(from day 1)***

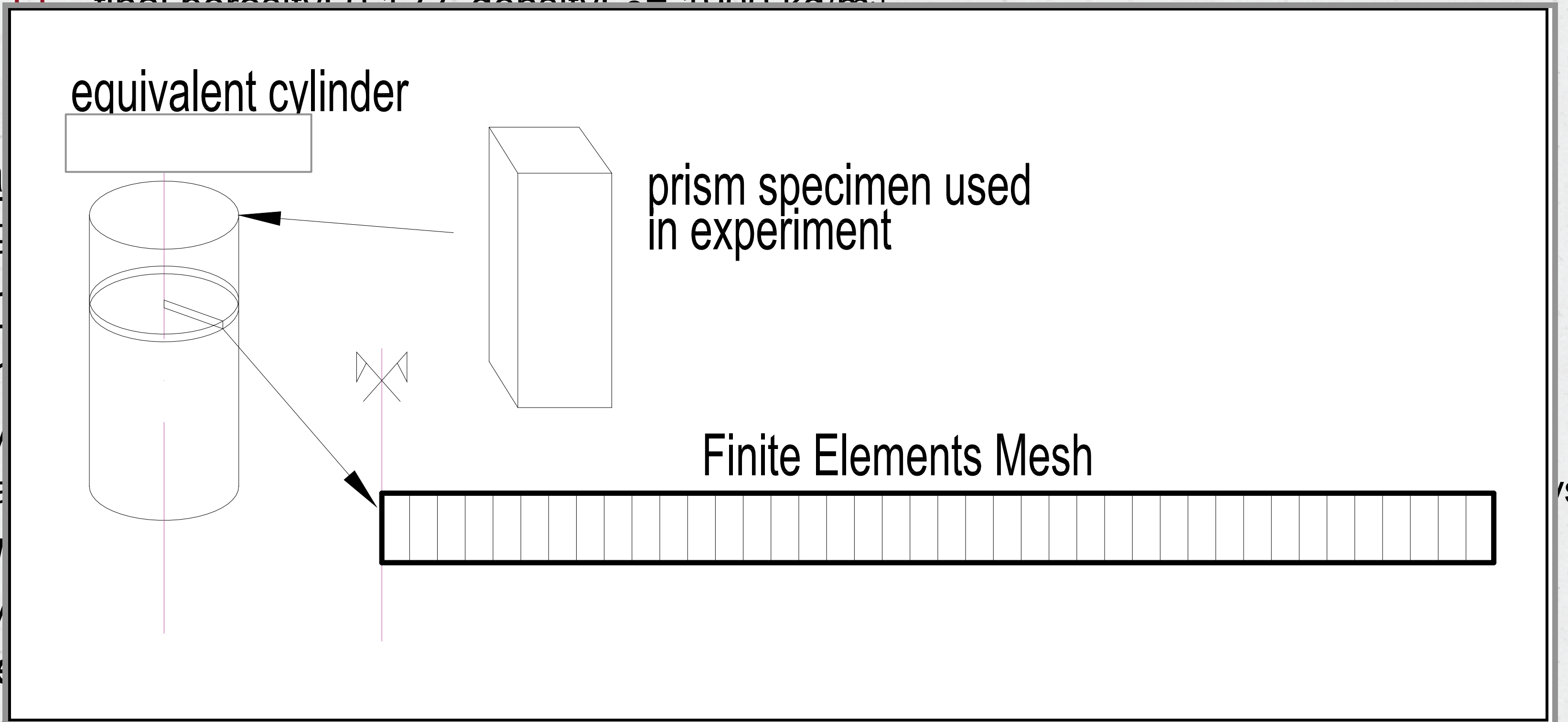
- convective heat and mass exchange: RH_{amb}=99.99%; α_c=2W/m^{2}K, β_c=0.01m/s

Sealed ***(for the first day and basic creep)***

- convective heat and mass exchange: no exchange
- surface mechanical load: load=4.9, 9.8 and 12.3 MPa at 7, 21, 28 and 90 days

Numerical example: tests of L'Hermite (1965)

- ✓ **Square prism** – 7x7x28 cm; equiv. cylinder ϕ=7.6 cm;
- ✓ Material: concrete C30
  - final porosity: 0.122, density: ρ= 1900 kg/m³



- ✓ Initia
  T_o= 29
- ✓ Bour

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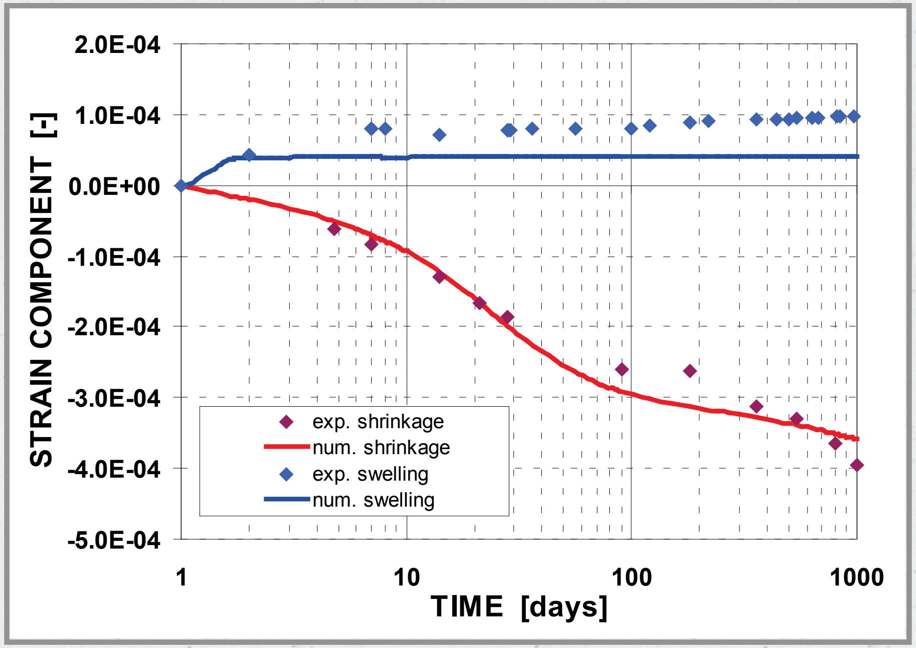
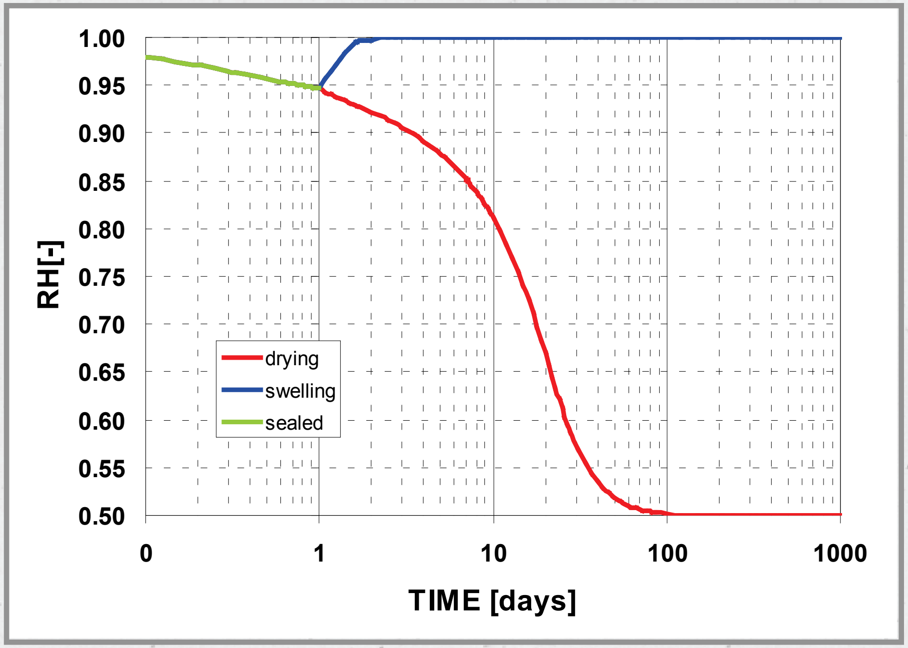
Seale

- convective heat and mass exchange: no exchange
- surface mechanical load: load=4.9, 9.8 and 12.3 MPa at 7, 21, 28 and 90 days

Numerical example: tests of L'Hermite (1965)

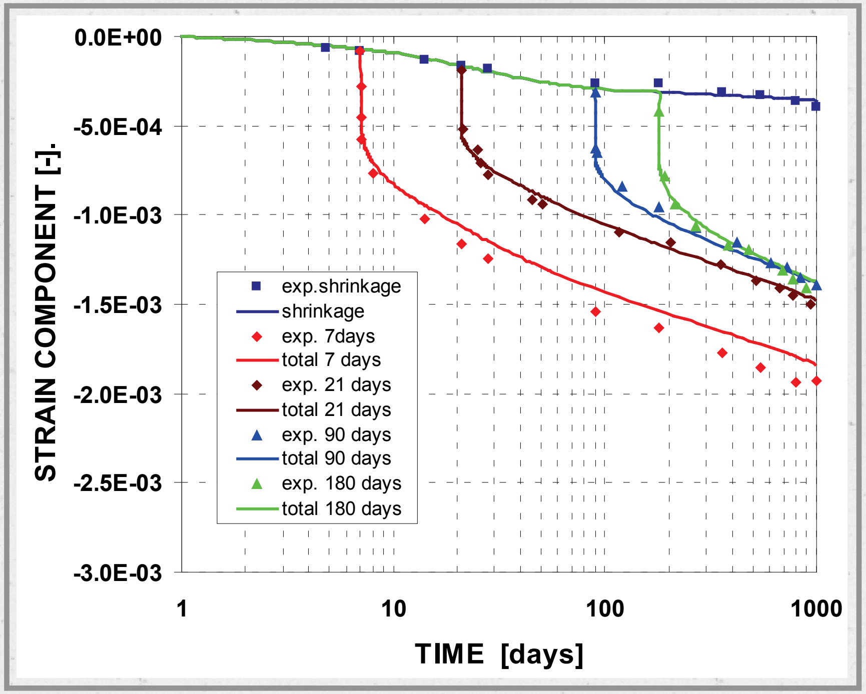


Swelling and shrinkage

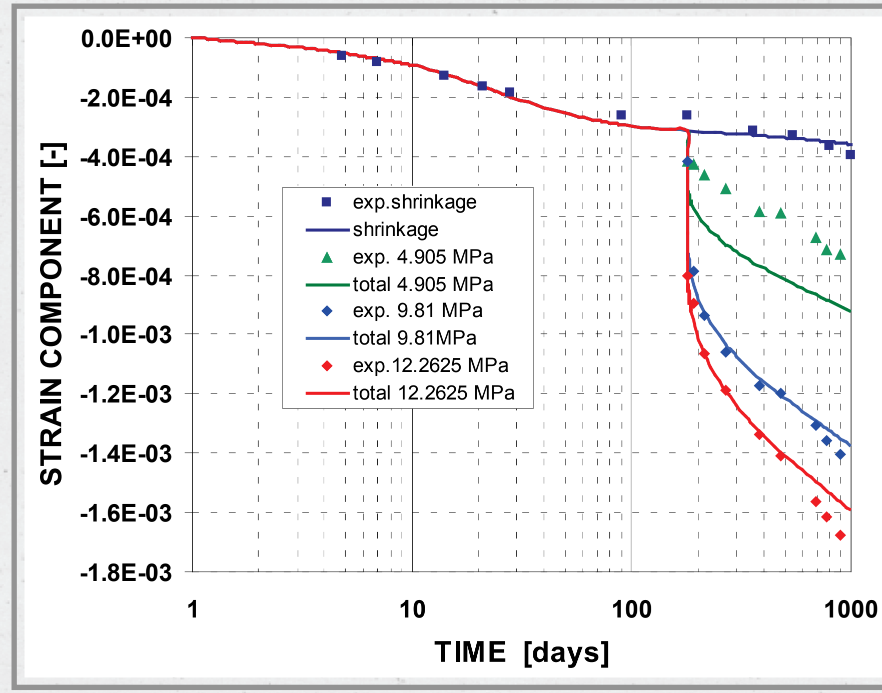


Relative humidity

Numerical example: tests of L'Hermite (1965)



Drying & Load (4.905 MPa)



Effect of load (180 days)

Numerical example: tests of L'Hermite (1965) – RH = var

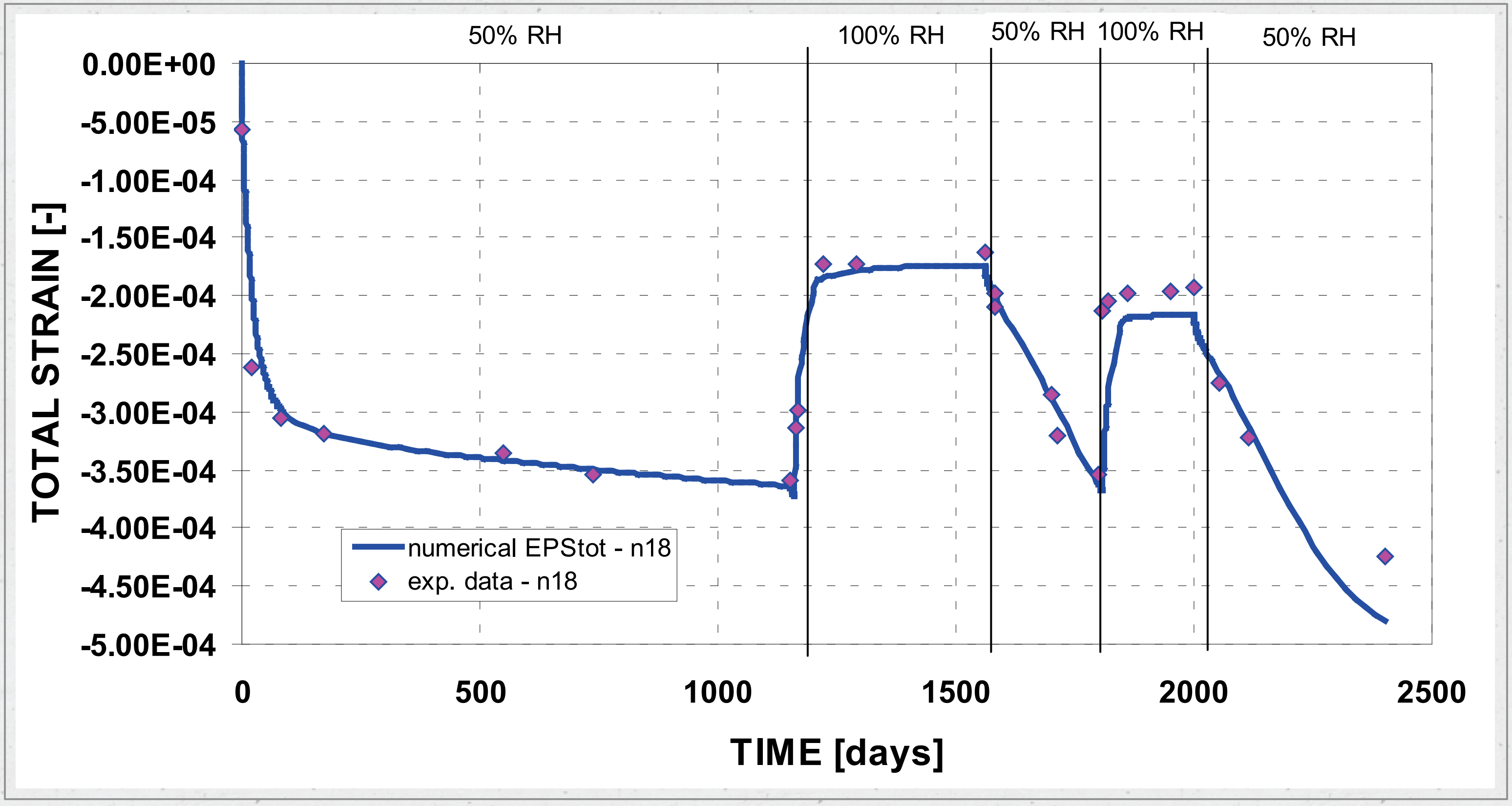
- ✓ **Square prism** – 7x7x28 cm; equiv. cylinder ϕ=7.6 cm;
- ✓ Material: concrete C30
  - ☐ - final porosity: 0.122, density: ρ= 1900 kg/m^3,
  - ☐ - intrinsic permeability: k_o= $1\cdot10^{-19}$ m^2,
  - ☐ - Young modulus: E= 28.5 GPa,
  - ☐ - water/cement ratio w/c=0.45, aggregate/cement ratio a/c=3.95
- ✓ Initial conditions:

  T_o= 293.15 K, φ_o= 99.8% RH, Γ_{hydr}=0.3;
- ✓ Boundary conditions:

  Shrinkage ***(cyclic conditions)***

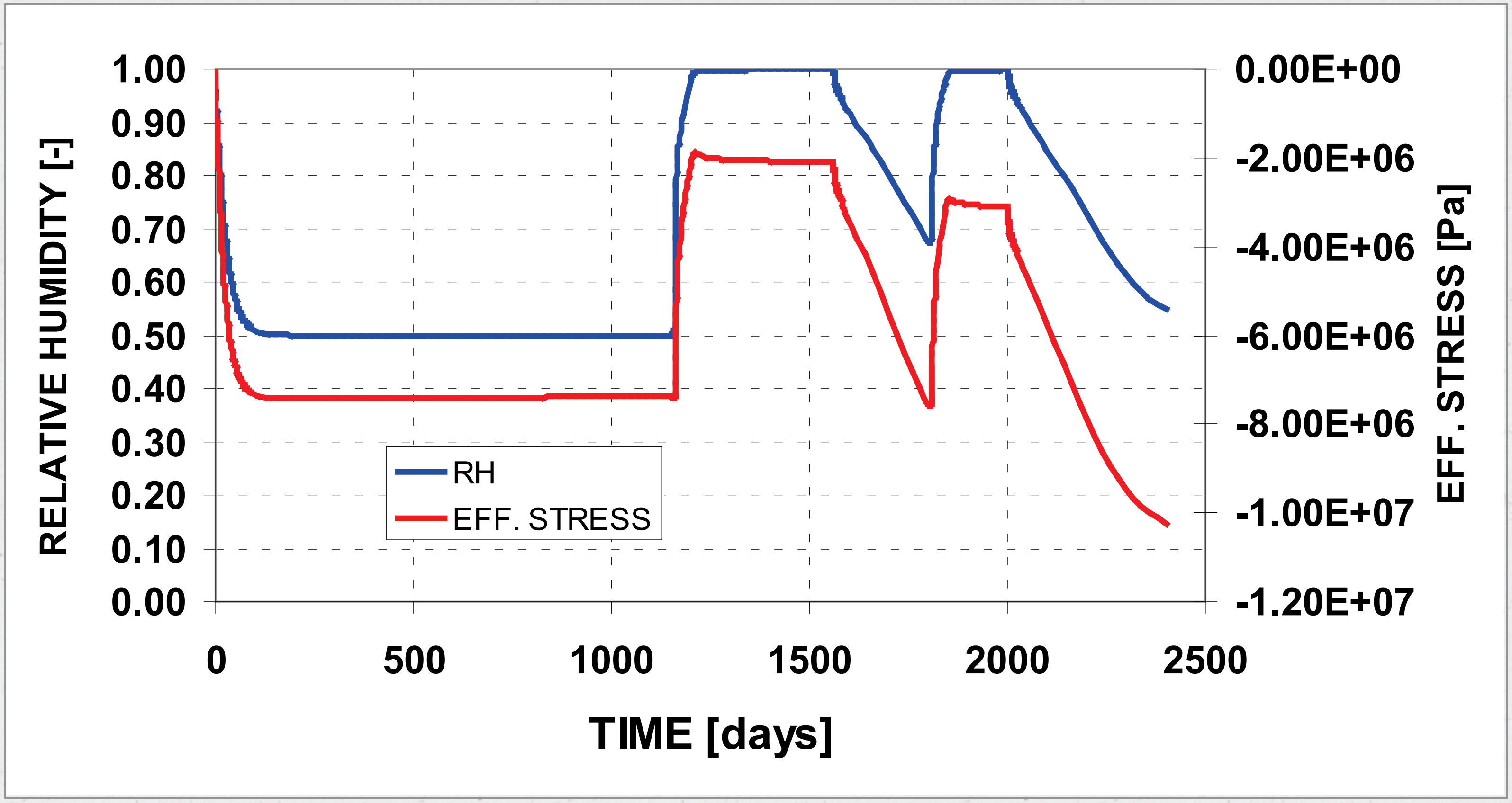
  - convective heat and mass exchange in air: α_c=2W/m^{2}K; β_c=0.00013 m/s; RH_{amb}=50%
  - convective heat and mass exchange in water: α_c=2W/m^{2}K; β_c=0.00026 m/s; RH_{amb}=99.9%

Numerical example: tests of L'Hermite (1965) – RH = var



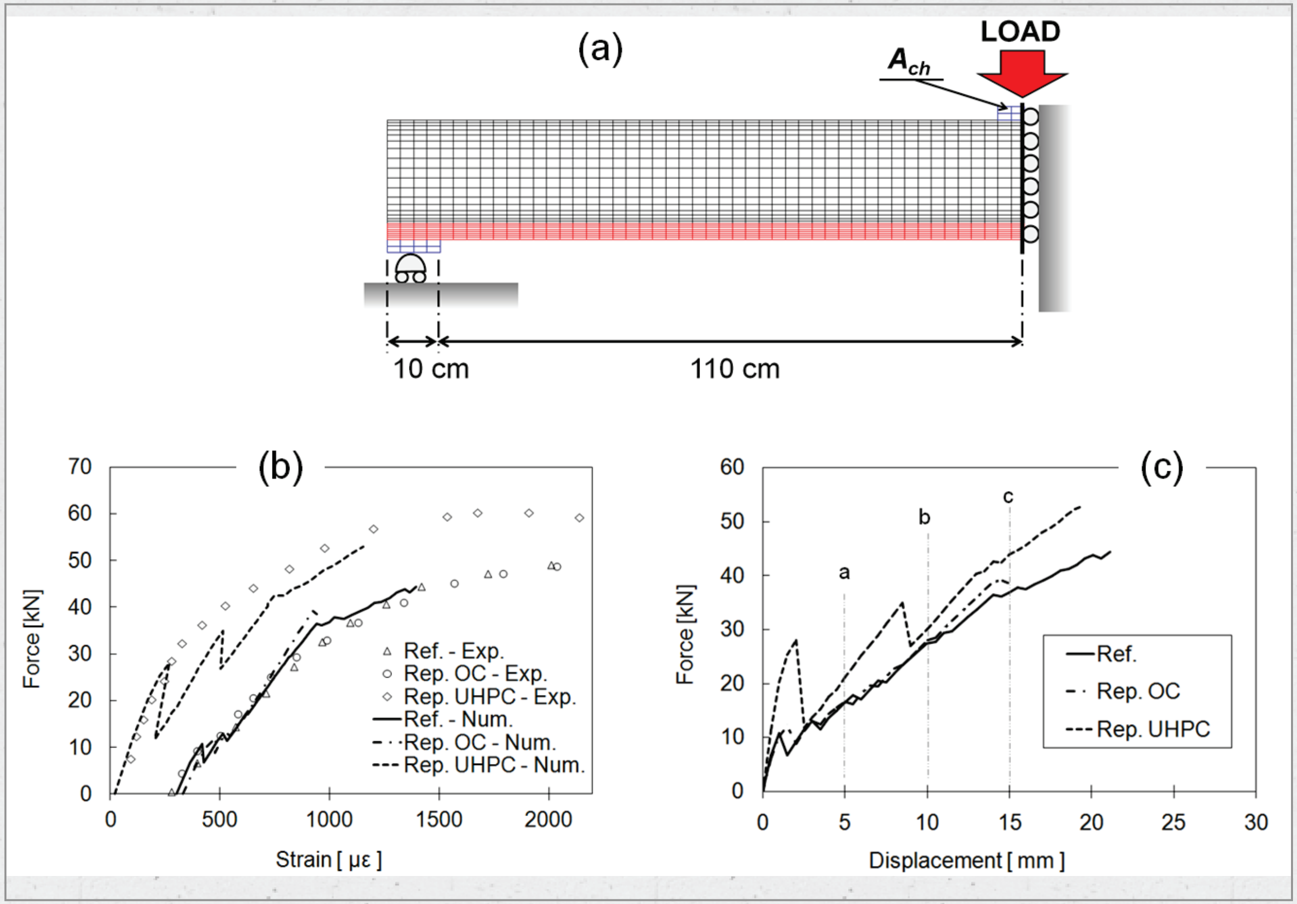
Total strain

Numerical example: tests of L'Hermite (1965) – RH = var



Relative humidity and Effective stress

Example of application: repaired beam



Mechanical boundary conditions and geometrical configuration for the 3-points bending test (a); Force versus averaged strain of the compressed fiber optic sensor (b); Force versus displacement curves (numerical results) (c)

Example of application:
concreting of a massive concrete structure

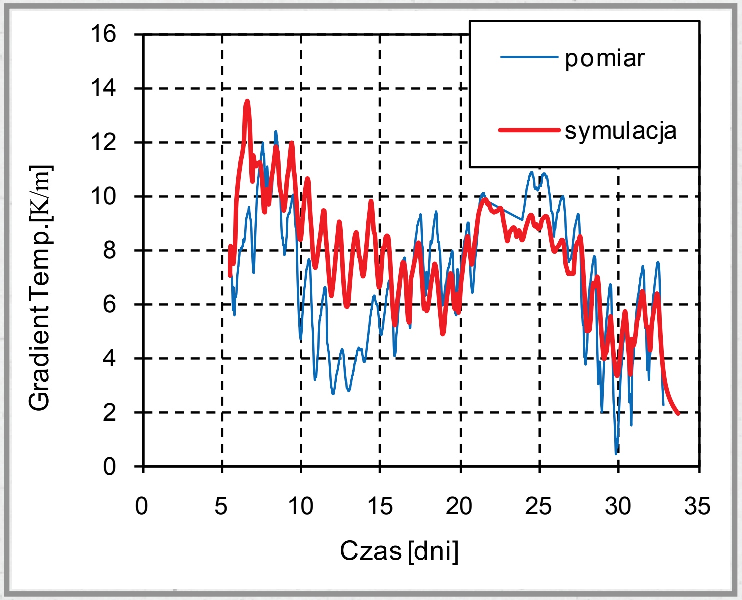
Bełchatów Power Station (Poland)

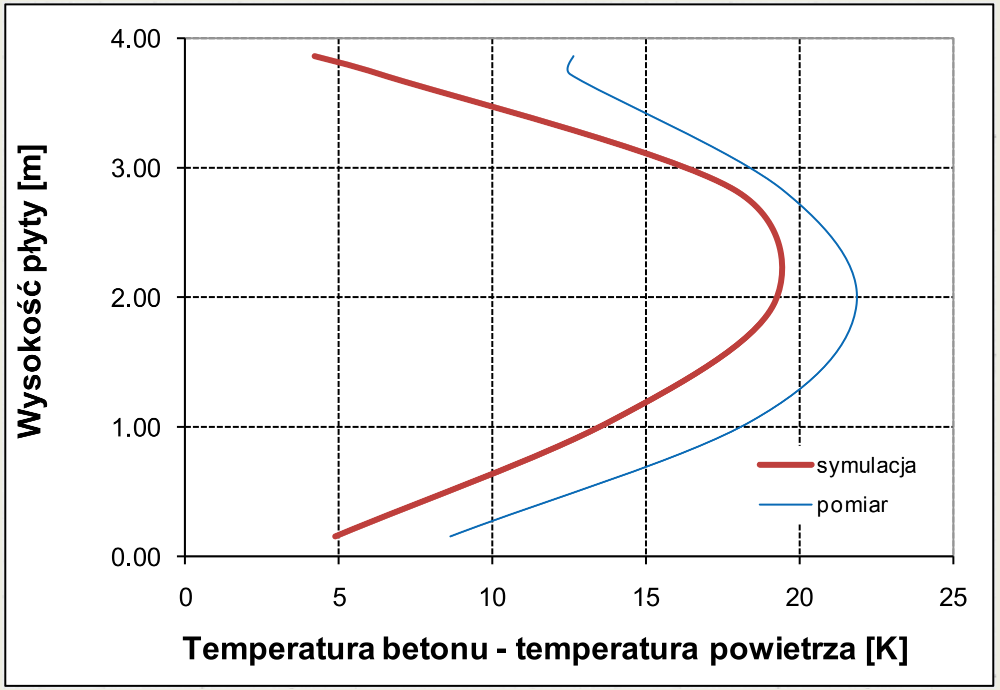
- Foundation: 98.8 m x 83.5 m with thickness of 2.5-4.5 m
- Volume: **27500** m^3, continous concreting of 6 days (200 m^3/h)

From

[Bujak W. et al. Budownictwo Technologie Architektura, 2007]

Example of application:
concreting of a massive concrete structure

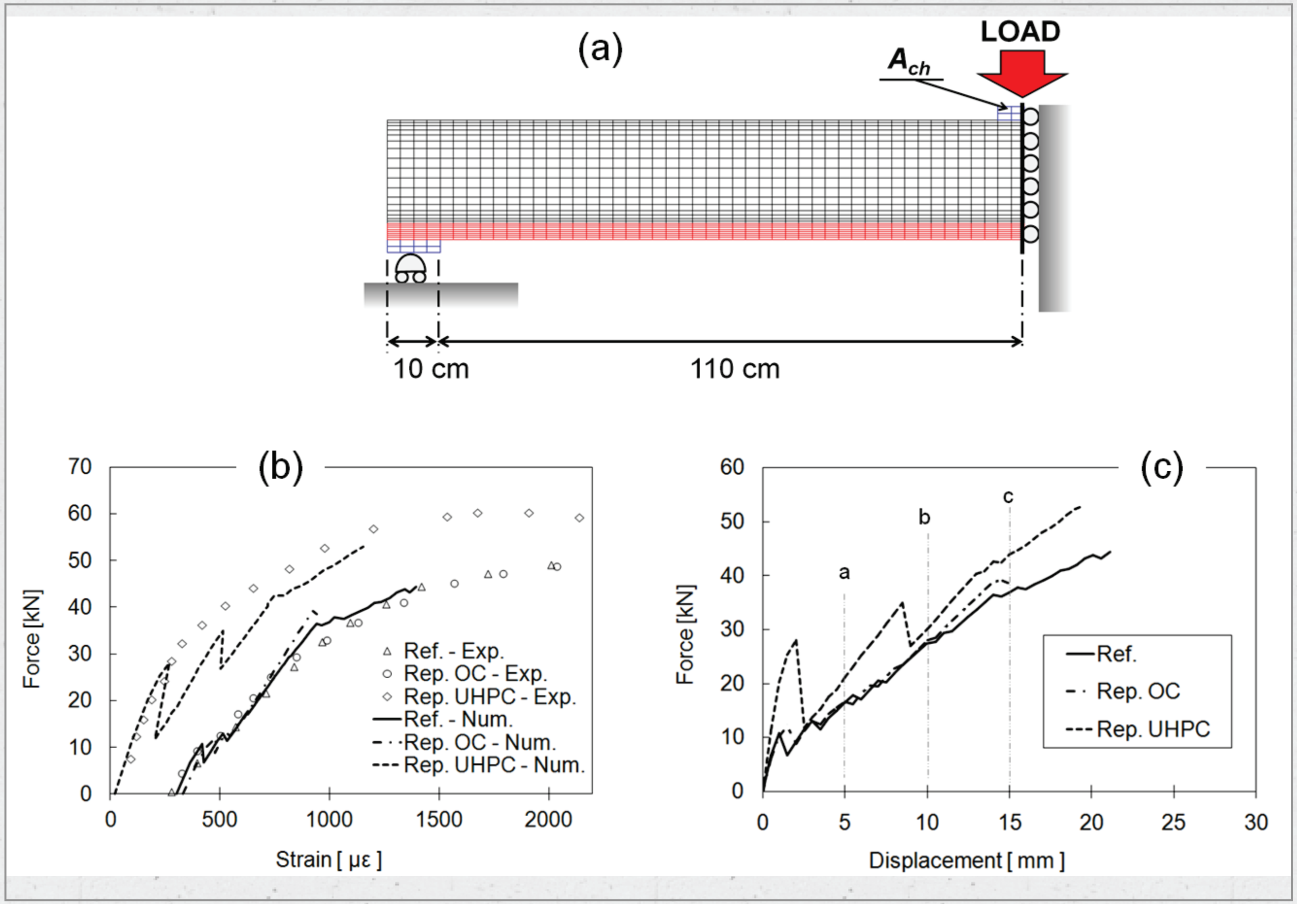




Maximal gradient

- ✓ measured: 12.4 K/m
- ✓ simulations: 13.5 K/m

Example of application: repaired beam



Mechanical boundary conditions and geometrical configuration for the 3-points bending test (a); Force versus averaged strain of the compressed fiber optic sensor (b); Force versus displacement curves (numerical results) (c)

Conclusions

- A general approach to modeling concrete as multiphase porous material by means the mechanics of multiphase porous media for the analysis of its thermo-hygral-chemical and mechanical behaviour has been presented.
- A mathematical model of concreto at early ages and beyond had been presented and experimentally validated
- Effective stresses are consequently used for description of concrete strains (shrinkage and creep)
- Hydration is described in the rate form to account for variable hygro-thermal environmental conditions
- Some examples of the model application has been presented

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Back to the list of presentations

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Modeling thermo mechanical behavior in massive concrete structure : Application to tunnel lining

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[1]Laboratoire 3SR (Grenoble), [2]LMT (Cachan), [3] CETU(Lyon)

CETU 3SR LMT Cachan

Industrial context

- Extension Paris subway line No.4
  - Final tunnel lining : 10m formwork (thickness ~50cm)
  - Shotcrete support
  - Tunnel lining = prevention of water inflow (no structural role)
- Objectives of the study
  - Calibration and validation of macroscopic model on global laboratory test
  - Blind crack prediction to test macroscopic modelling of early age cracking

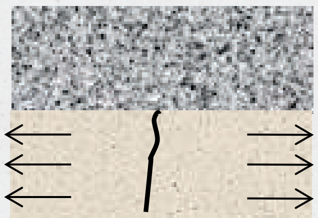
Tunnel lining formwork

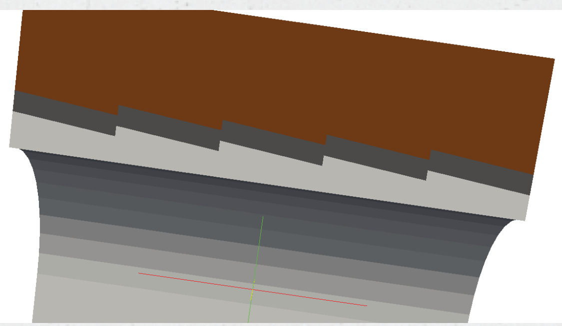
Cutting machine (support)

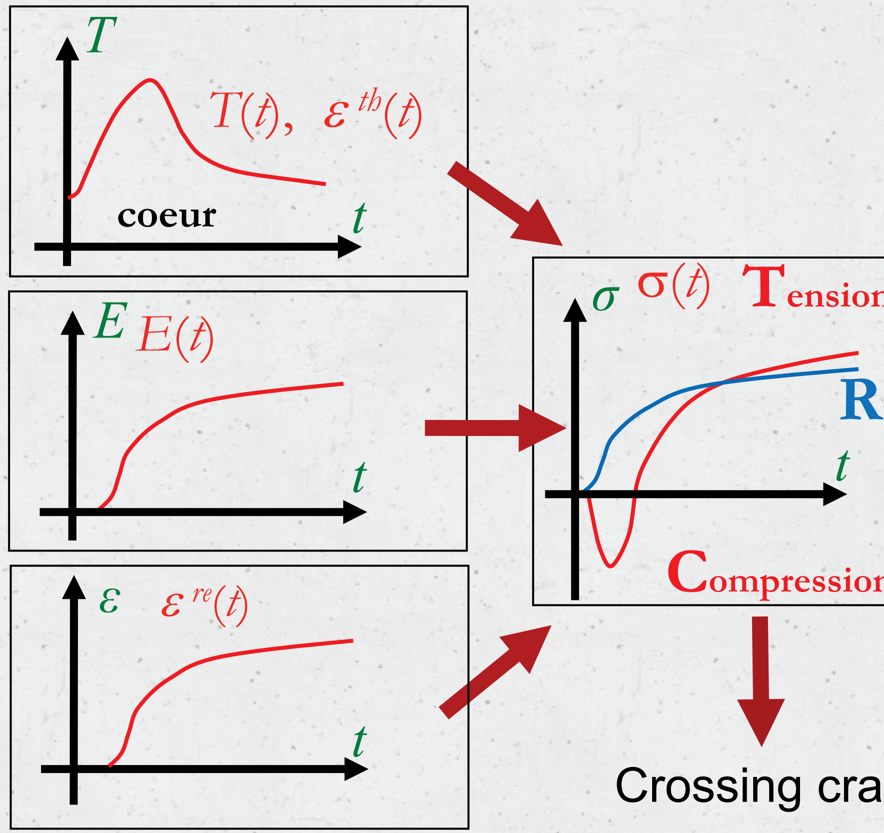
Scientific issues

Cracking mechanism: restrained shrinkage

- ✓ Thermal and autogenous restrained shrinkage







OUTLINE

- Model presentation
  - Thermal model
  - Mechanical model
- Model parameters identification
  - Focus on activation energy
  - Validation on a global laboratory test
  - Focus on coupling between creep and damage
- Application to tunnel lining
  - Classification of involved phenomena

Chemo-thermal model

Heat equation with source

$$C\dot{T} = \nabla\left(k\nabla T\right) + L\dot{\xi}$$

C = C (ξ, T, concrete mix) = Volumetric thermal capacity
k = k (ξ, T, concrete mix) = Thermal conductivity
L = L (concrete mix) =Total heat release

Hydration degree evolution

[Regourd et al., 80] [Lackner et al., 04] [Ulm et al., 98]

$$\dot{\xi} = \tilde{A}(\xi)\exp\left(-\frac{E_a}{RT}\right)$$

Mechanical parameters evolution

[De Schutter et Taerwe, 96]

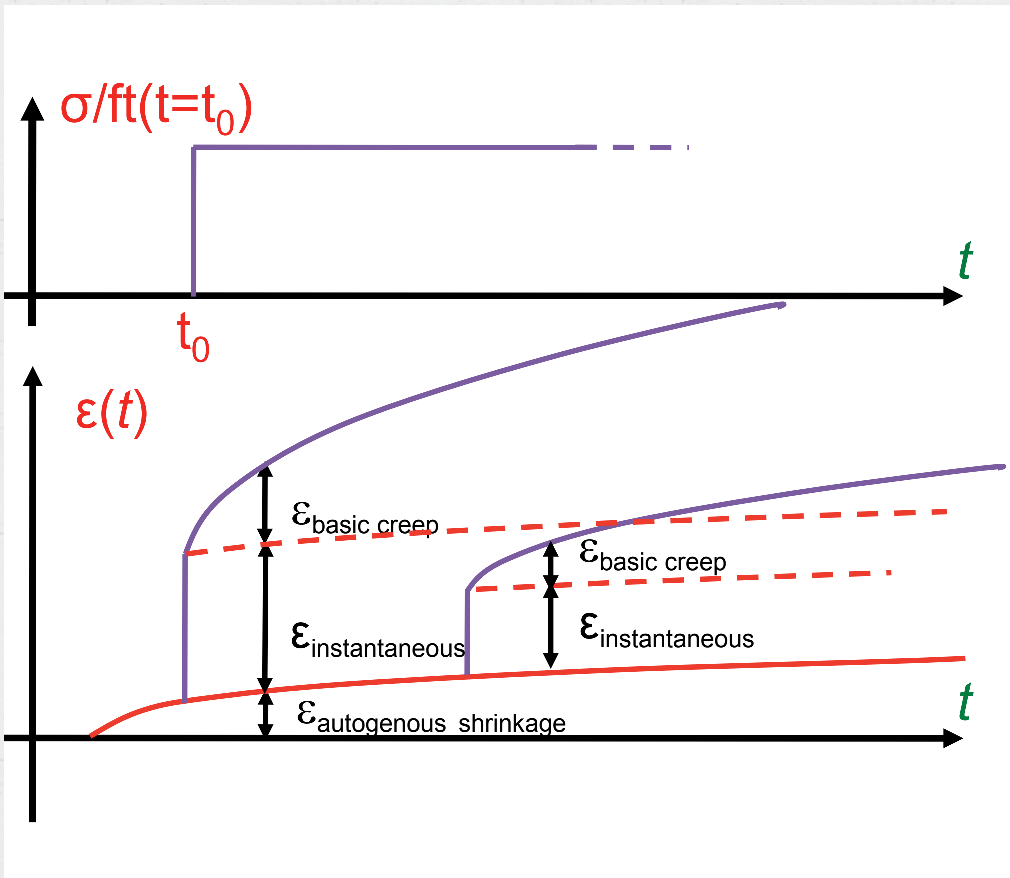
$$X(\xi) = X_\infty\left(\frac{\xi(t)-\xi_0}{\xi_\infty-\xi_0}\right)^{a_X} \qquad pour\ \xi > \xi_0$$

Autogeneous and thermal strains

[Laplante, 93][Mounanga et al., 06][Ulm et al. 98]

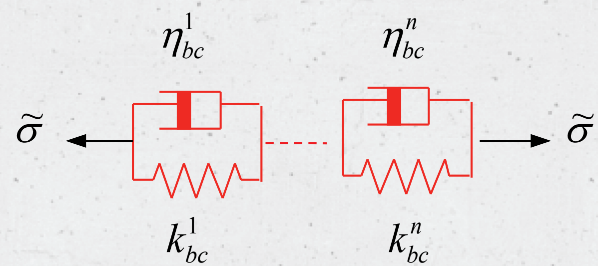
$$\dot{\varepsilon}_{ij}^{au} = \kappa\dot{\xi}\delta_{ij} \quad pour\ \xi > \xi_0 \qquad\qquad \dot{\varepsilon}_{ij}^{th} = \alpha\dot{T}\delta_{ij}$$

Creep model



Rheological modelling

- ✓ Kelvin-Voigt chains (KV) :



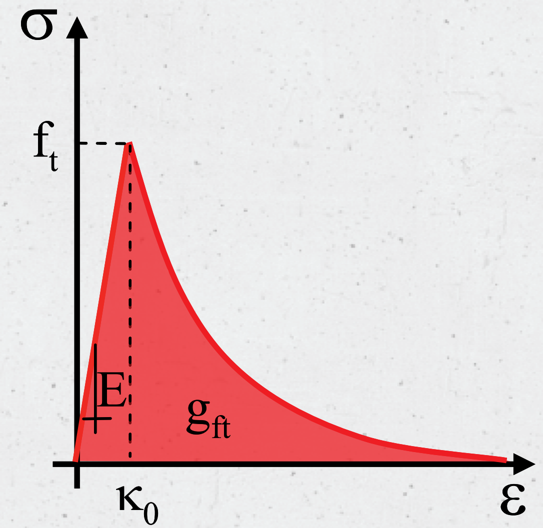
- ✓ Differential equation of one KV:

$$\tau_{bc}^{i}\ddot{\varepsilon}_{bc}^{i} + \left(\tau_{bc}^{i}\frac{\dot{k}_{bc}^{i}(\xi,T)}{k_{bc}^{i}(\xi,T)} + 1\right)\dot{\varepsilon}_{bc}^{i} = \frac{\dot{\tilde{\sigma}}}{k_{bc}^{i}(\xi,T)}$$

- ✓ Characteristic time of one KV:

$$\tau_{b}^{i} \underset{c}{=} \frac{\eta_{b}^{i}\ (\xi)}{k_{b}^{i}\ (\xi)} = c \quad o$$

Mechanical model



Tensile behavior law of cement paste

Strains decomposition

$$\dot{\tilde{\boldsymbol{\sigma}}} = \mathbf{E}(\xi)\dot{\boldsymbol{\varepsilon}}_{el} = \mathbf{E}(\xi)\left(\dot{\boldsymbol{\varepsilon}}_{tot} - \dot{\boldsymbol{\varepsilon}}_{bc} - \dot{\boldsymbol{\varepsilon}}_{ttc} - \dot{\boldsymbol{\varepsilon}}_{au} - \dot{\boldsymbol{\varepsilon}}_{th}\right)$$

Equivalent strain [Mazars,84][Mazzoti, 03]

$$\tilde{\varepsilon} = \sqrt{\langle \boldsymbol{\varepsilon}_e \rangle_+ : \langle \boldsymbol{\varepsilon}_e \rangle_+ + \beta \langle \boldsymbol{\varepsilon}_{bc} \rangle_+ : \langle \boldsymbol{\varepsilon}_{bc} \rangle_+}$$

Damage threshold

$$\kappa_0 = \frac{f_{t\infty}}{E_\infty} \cdot \left(\frac{\xi - \xi_0}{\xi_\infty - \xi_0} \right)^{c-a}$$

Damage variable evolution [Nechnech, 00]

$$D_t(\tilde{\varepsilon}) = 1 - \frac{\kappa_0}{\tilde{\varepsilon}}\left[(1 + a_t)\ \exp\left(-b_t\ (\tilde{\varepsilon} - \kappa_0)\right) - a_t\ \exp\left(-2b_t\ (\tilde{\varepsilon} - \kappa_0)\right)\right]$$

Regularization by fracture energy [Hillerborg, 76][De Schutter, 99]

OUTLINE

- Model presentation
  - Thermal model
  - Mechanical model
- Model parameters identification
  - Focus on activation energy
  - Validation on a global laboratory test
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Global calibration strategy

« Standardized » test

Active ring test

Hydration

Creep

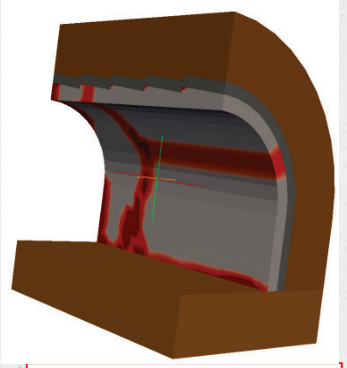
Shrinkage

Chemo-thermo-mechanical model

Thermal strains

Mechanical prop. Evol.

Coupling + Representatives boundaries conditions



Structures modelling

Hydration degree

Hydration degree evolution [Van Breugel, 97]

$$\xi(t) = \frac{m_{ch}(t)}{m_{can}(t=0)}$$

Identification thanks to calorimetry

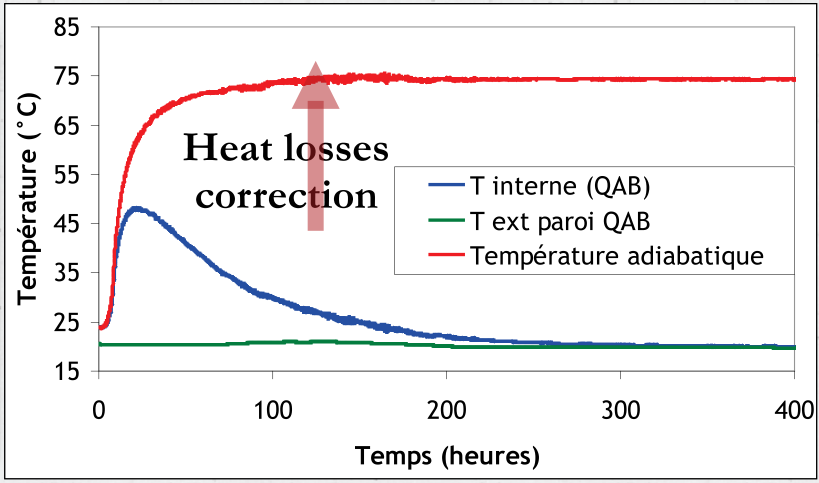
$$\xi(t) = \alpha(t) \times \xi_\infty = \frac{m_{ch}(t)}{m_{ch}(t=\infty)} \xi_\infty$$

Essai QAB (LCPC)

Semi-adiabatic calorimetry

Principle : reaction progression proportional to heat release

Determination of adiabatic temperature



Activation energy

Chemo thermal model

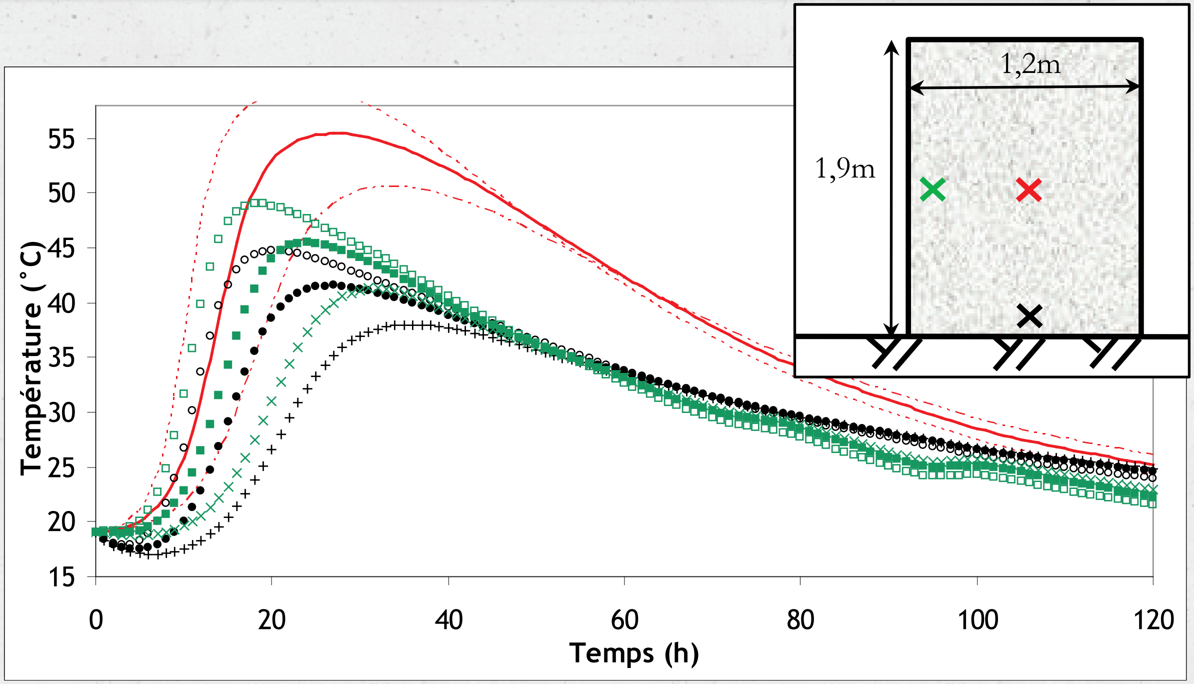
$$C\dot{T} = \nabla(k\nabla T) + L\dot{\xi}$$

$$\dot{\xi} = \tilde{A}(\xi)\exp\left(-\frac{E_a}{RT}\right)$$

C = C (ξ, T, concrete mix) = Volumetric thermal capacity
k = k (ξ, T, concrete mix) = Thermal conductivity
L = L (concrete mix) =Total heat release

Activation energy influence

Low variation ((± 2%)
-> high influence in predicted temperature



Activation energy

Chemo thermal model

$$C\dot{T} = \nabla\left(k\nabla T\right) + L\dot{\xi}$$

$$\dot{\xi} = \tilde{A}(\xi)\exp\left(-\frac{E_a}{RT}\right)$$

C = C (ξ, T, concrete mix) = Volumetric thermal capacity
k = k (ξ, T, concrete mix) = Thermal conductivity
L = L (concrete mix) =Total heat release

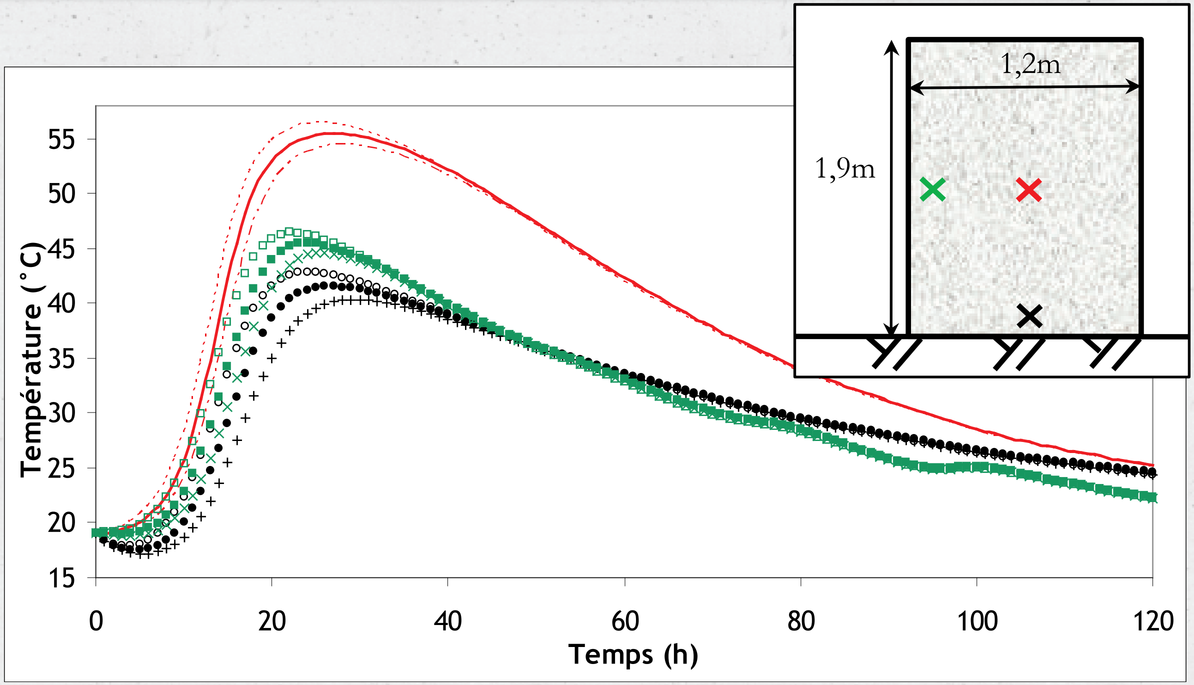
Influence of couple $A(\xi)$ and E_a

High variation(±25%): low influence [Briffaut et al. 12]

Cause :

$$A(t) = \xi_\infty \frac{dT^{ad}/dt}{T_\infty^{ad} - T_0^{ad}} \exp\left(\frac{Ea}{RT(t)}\right)$$

Approximated value is sufficient [Kishi et Maekawa, 94][Schindler, 04]



Global calibration strategie

« Standardized » test

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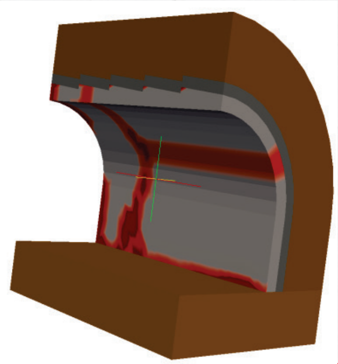
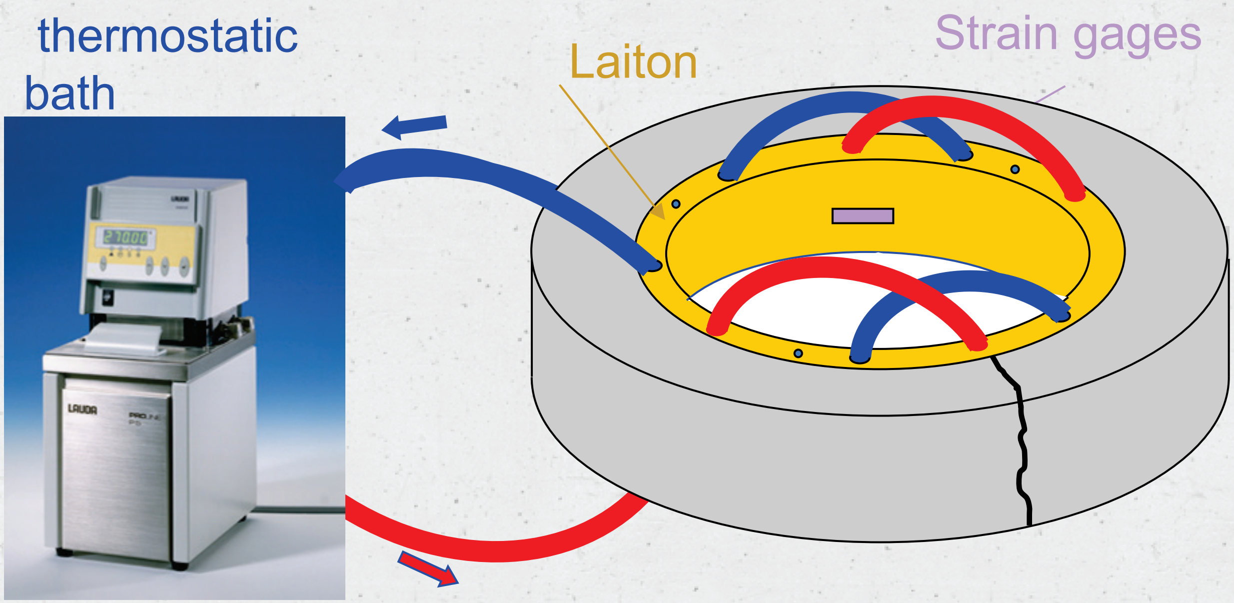


Structures modelling

Thermal ring test



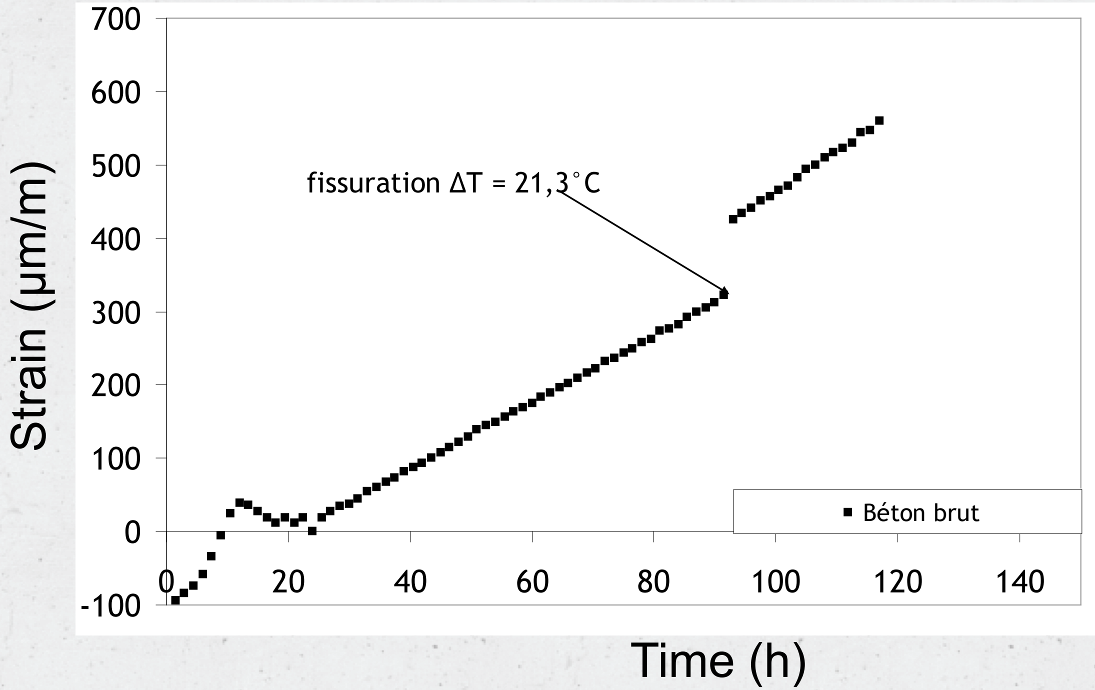
Ring test before casting

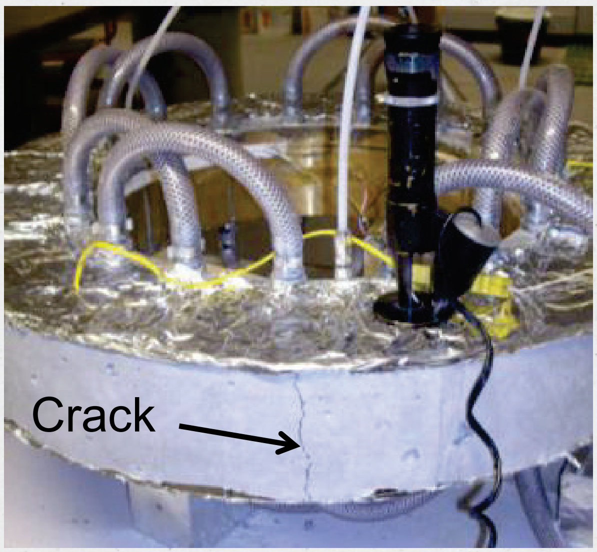
Ring test after casting

Thermal ring test : actif

- ✓ **Principe:** thermal expansion of metallic ring
- ✓ **Advantages:**
  - Axisymmetric geometry
  - Temperature, creep, rupture,…
- ✓ **Complex test -> Model benchmarking?**

Thermal ring test : results





Cracked concrete ring

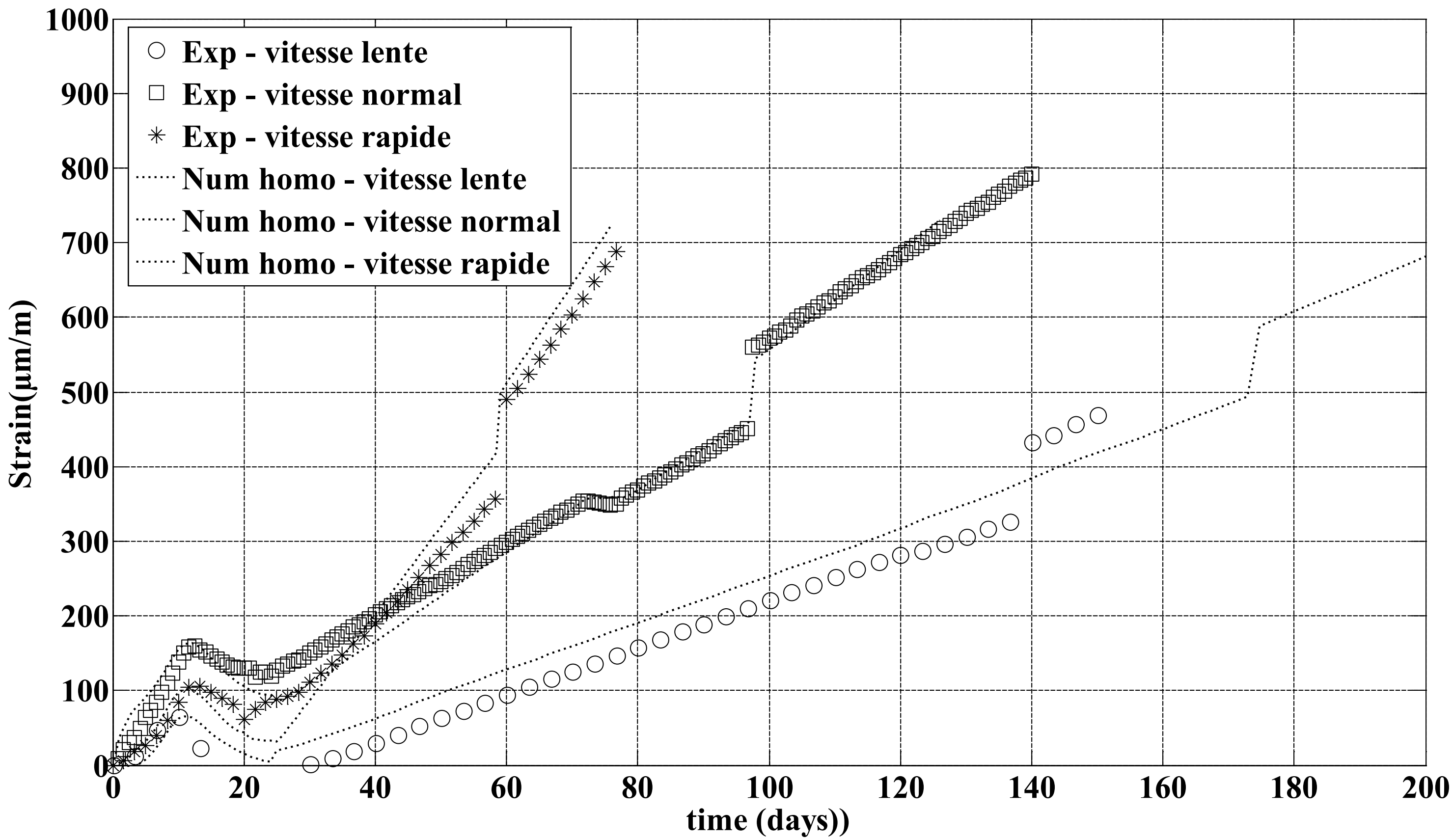
Experimental results

- ✓ Temperature brass and concrete
- ✓ Deformations measured on the inside radius of brass (low dispersion)
- ✓ **Strain gap: cracking of the concrete ring**
- ✓ Study of rebars, construction joints [Briffaut et al. 11]

Model & parameters validation

Equivalent strain [Mazars,84][Mazzoti, 03]

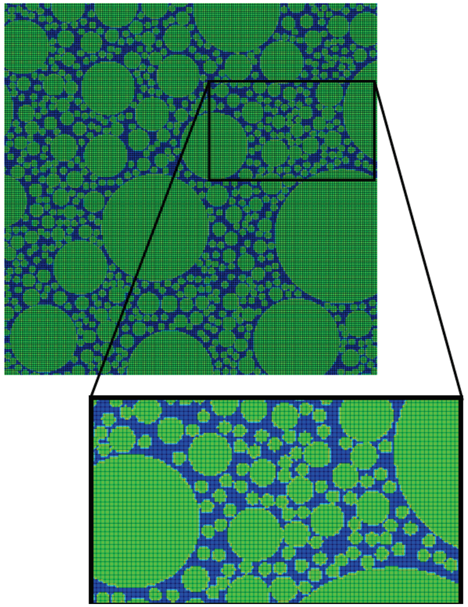
$$\tilde{\varepsilon} = \sqrt{\langle \boldsymbol{\varepsilon}_e \rangle_+ : \langle \boldsymbol{\varepsilon}_e \rangle_+ + \beta \langle \boldsymbol{\varepsilon}_{bc} \rangle_+ : \langle \boldsymbol{\varepsilon}_{bc} \rangle_+}$$



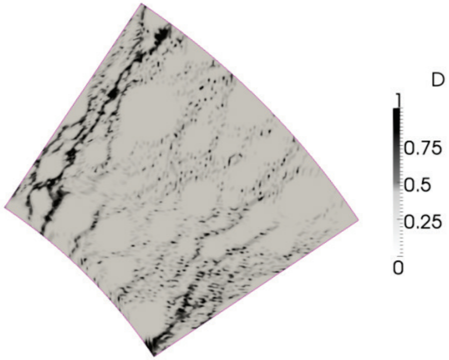
Model & parameters validation

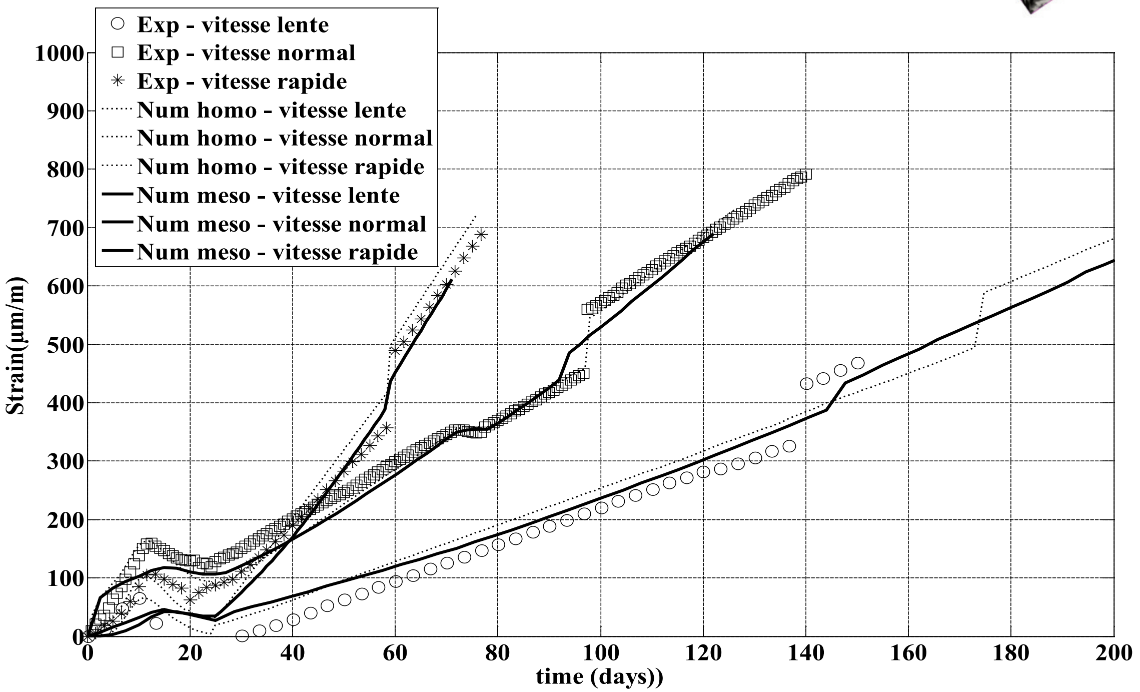
Equivalent strain [Mazars,84][Mazzoti, 03]

$$\tilde{\varepsilon} = \sqrt{\langle \boldsymbol{\varepsilon}_e \rangle_+ : \langle \boldsymbol{\varepsilon}_e \rangle_+}$$



Mesoscopic mesh [Nguyen et al., 10]





OUTLINE

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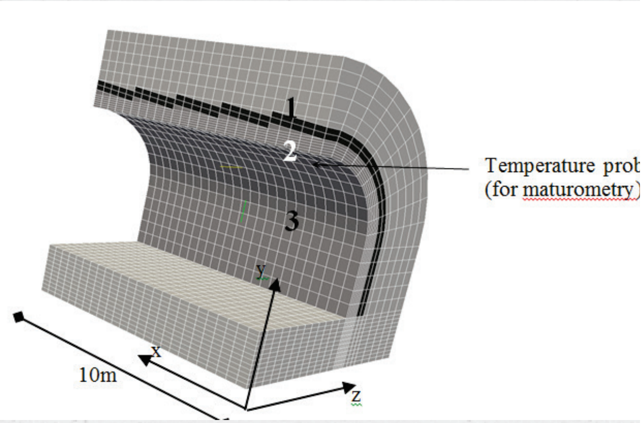
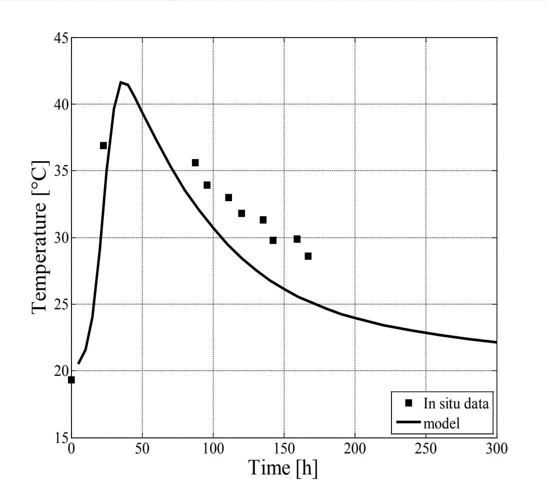
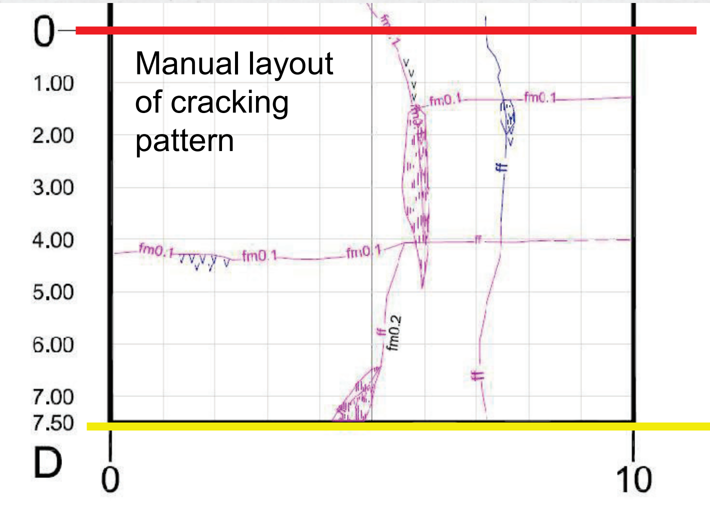
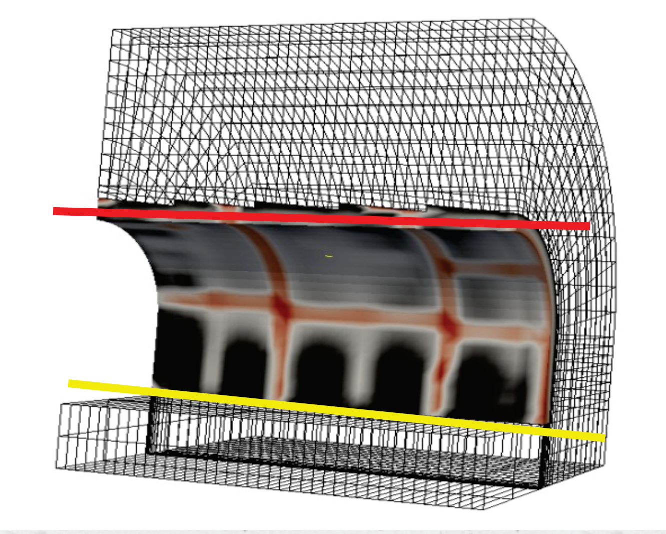
Tunnel lining simulations



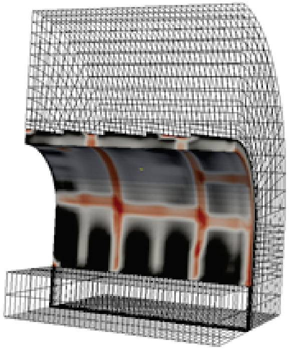




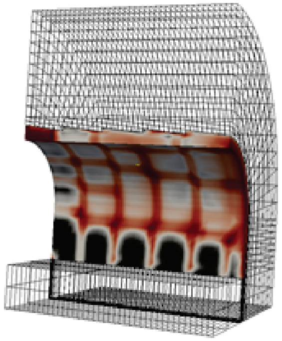
- Decrease of tensile strength due to scale effect (40%) [Van Vliet and Van Mier, 00]: otherwise no crack is predict
- Coupling coefficient : 0,4
- Cracking pattern similar to the one observed
  - Vertical crossing cracks
  - Horizontal crack



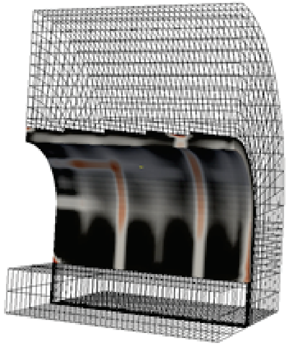
Phenomenon classification



Damage field due to both thermal and autogenous shrinkage after 360 hours
(in considering creep)



Damage field due to both thermal and autogenous shrinkage after 360 hours
(in neglecting creep)



Damage field due to thermal shrinkage after 360 hours

High influence of creep (as expected)

Main phenomena involve in cracking : Thermal evolution

Conclusion

- A global strategy coupling complex and innovative test with chemo-thermo mechanical modelling was used to identify a macroscopic concrete model
  - With this model an approximate value of activation energy is sufficient but the whole set of parameters validation required a global laboratory test
  - Coupling coefficient between creep and damage is explained by strains incompatibilities but remains still to calibrate for macroscopic modelling
- Blind cracking prediction on a real structure is very closed to the observed pattern
  - Main phenomena involves in tunnel lining cracking is thermal shrinkage

TU 1404
COST ACTION

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TU 1404 COST ACTION

THERMO-MECHANICAL BEHAVIOUR OF CONCRETE STRUCTURES: MATERIAL CHARACTERIZATION, IN SITU MONITORING AND NUMERICAL SIMULATION

Rui Faria - University of Porto, Faculty of Engineering, Portugal
Miguel Azenha - University of Minho, School of Engineering, Portugal
José Conceição - University of Porto, Faculty of Engineering, Portugal

U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

CONSTRUCT

Universidade do Minho Escola de Engenharia

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Initial considerations

- In concrete structures the heat released by the cement hydration reactions, combined with the low thermal conductivity of concrete, promotes significant temperature rises and thermal gradients.
- Combined with external and internal restraints to the free deformation of concrete, these thermal effects may lead to tensile stresses during the concrete early ages, responsible for the occurrence of cracking.
- This is particularly severe when dealing with:
  - Massive concrete structures (dams, thick slabs, etc.)
  - High cement contents in the concrete mix
  - Fast construction

(...)

- Presently thermo-mechanical (T-M) numerical modelling of concrete structures, at a macro-scale level, is feasible with many available advanced Finite Element codes.

- The main difficulty lies on the susceptibility of T-M predictions to the material parameters and boundary conditions (frequently difficult to assess) that are considered in the analyses.

- These difficulties can be minimized by using as much as possible:
  - Suitable experimental characterization of concrete T-M properties (macro-scale).
  - *In situ* monitoring of concrete temperatures and strains, for adjustment of the model and validation of results.

Contents

Thermal problem

$$k\nabla \cdot (\nabla T) + \dot{Q} = \rho c \dot{T}$$

Arrhenius Law

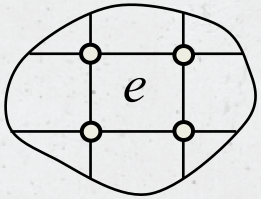
$$\dot{Q} = a \; f(\alpha) \, e^{-E_a/(RT)}$$

- **Boundary conditions (convection-radiation):** $q = h_{cr} \, (T_b - T_a)$

- **Nonlinear problem on T (solved via the N-R method)**

$\Rightarrow$ *Geometrical discretization (FEM)*

$$T = \boldsymbol{N} \, \boldsymbol{T}^e$$



$\Rightarrow$ *Temporal discretization (backward-Euler)*

$$\dot{T}_{n+1} = (T_{n+1} - T_n)/\Delta t$$

Mechanical problem

- The mechanical model is activated after the thermal one, from which it gets the temperatures, indispensable for computing the concrete strains and also the evolving material properties.
- Concrete stresses are evaluated via a viscoelastic linear model, which accounts for basic creep and material ageing.

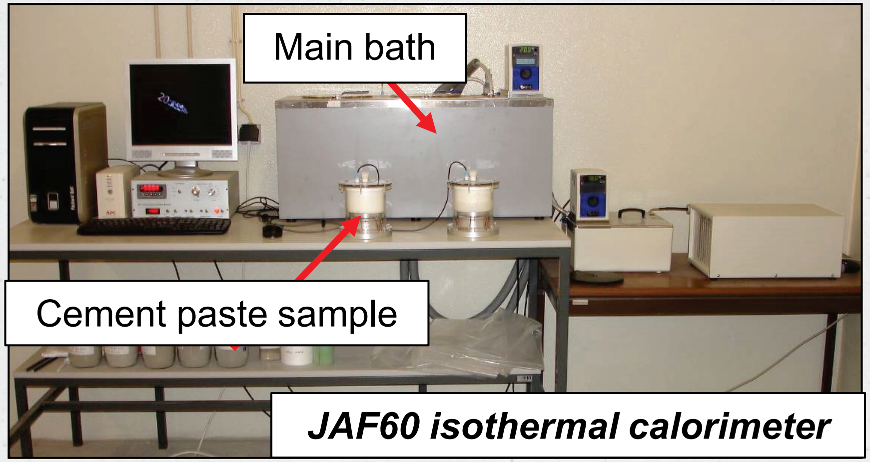
- Double Power Law

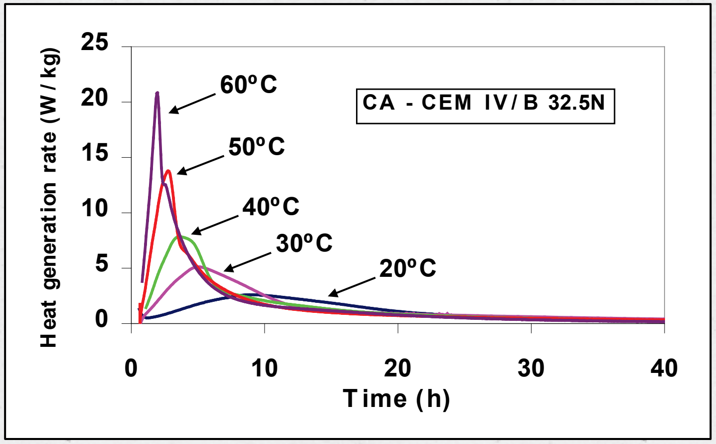
$$J(t,t') = \frac{1}{E_0(t')} + \frac{\phi_1}{E_0(t')}(t')^{-m}(t-t')^n$$

- Evolutions of $f_c(t)$, $f_{ct}(t)$ and $E_c(t)$ are characterized in the lab at a temperature T_{ref}, and corrected for the temperature history at each integration point using the Equivalent Age concept:

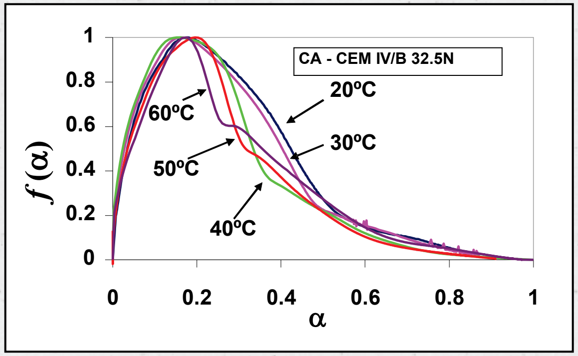
$$t_{eq} = \int_0^t e^{-\frac{E_a}{R}\left(\frac{1}{T(\tau)}-\frac{1}{T_{ref}}\right)} d\tau$$

Characterization of heat generation





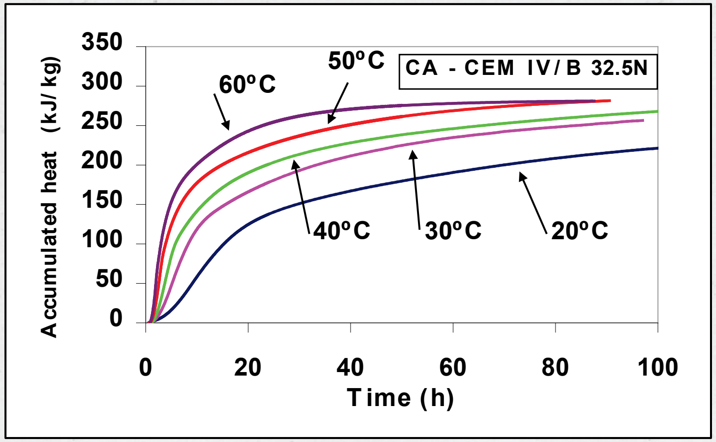
$$\dot{Q} = a\, f(\alpha)\, e^{-E_a/(RT)}$$



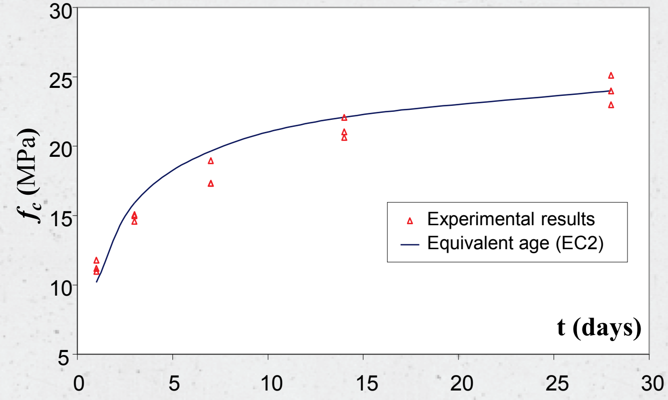
$a = 1.74994\times10^{9}$ W

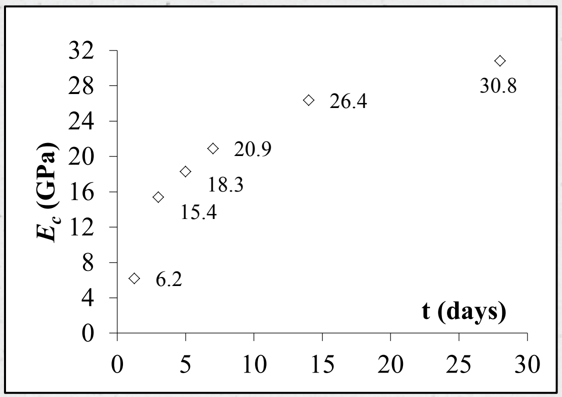
$E_a = 3.6509$ kJ mol^{-1}

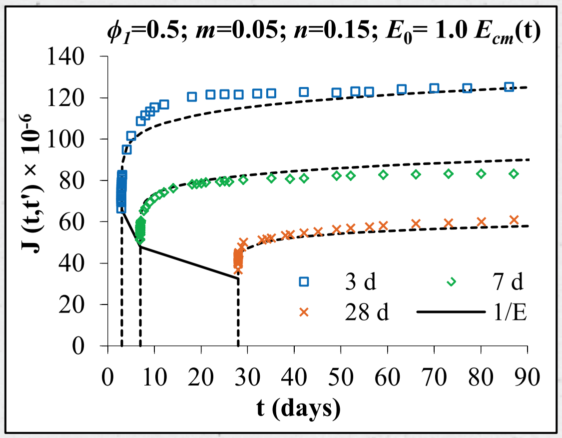
$Q_\infty = 279.5$ kJ kg^{-3}



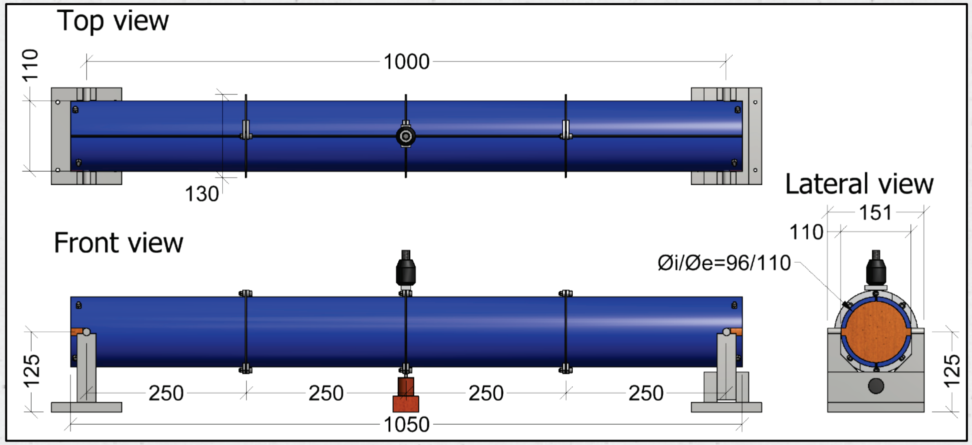
Characterization of mechanical properties

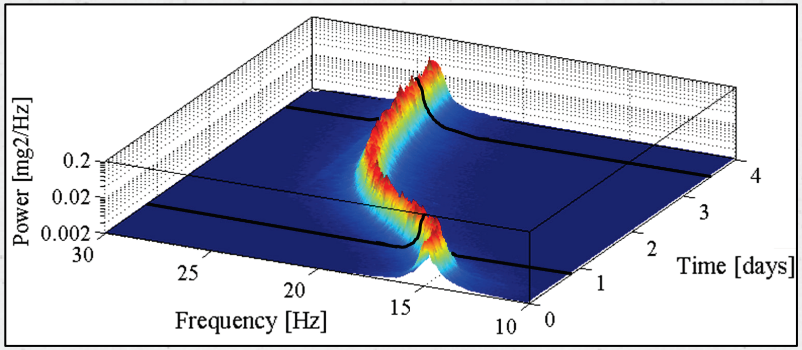


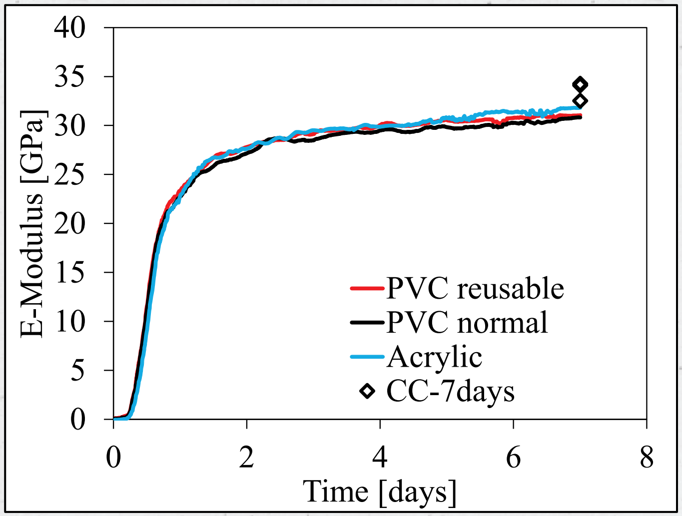




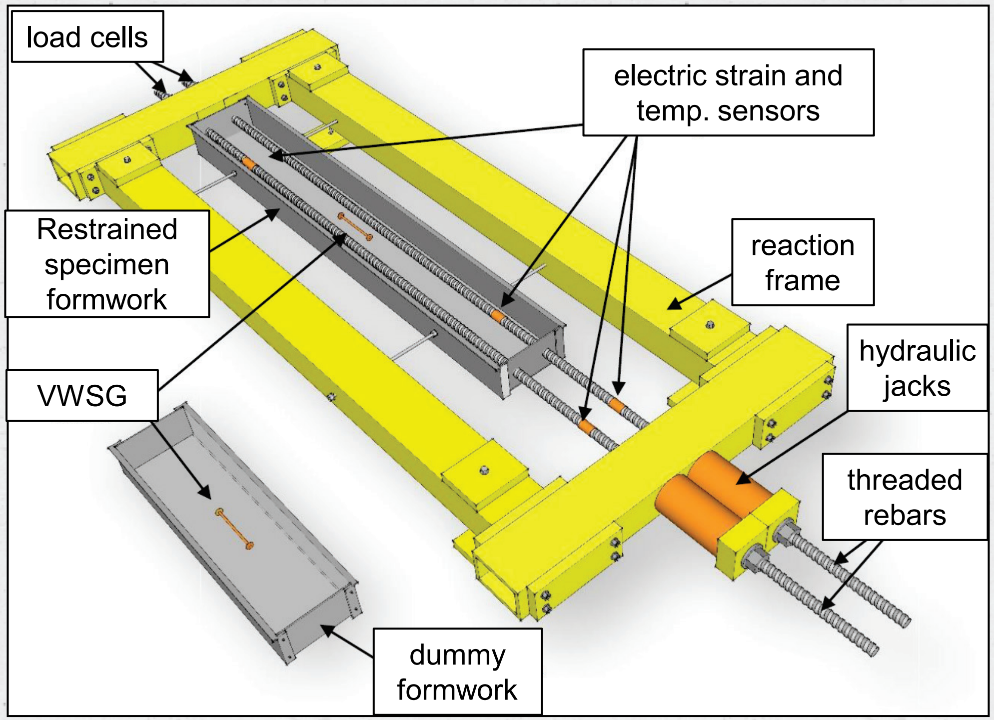
EMM-ARM for continuous measurement of E_c

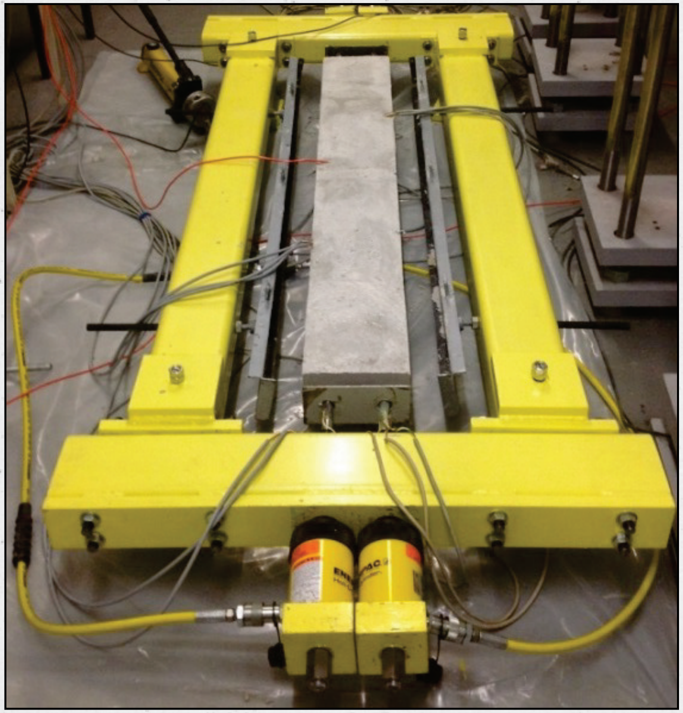






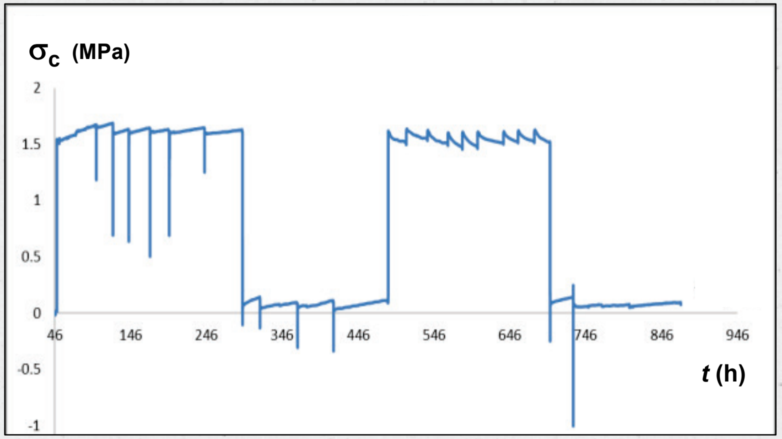
Novel method for assessing concrete tensile creep - Variable Restraint Frame (VRF)

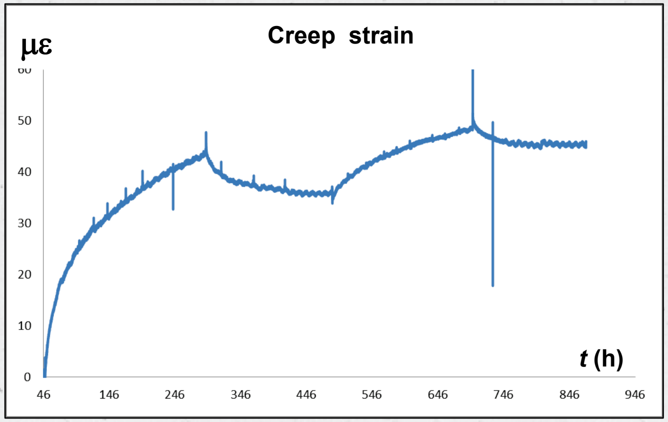




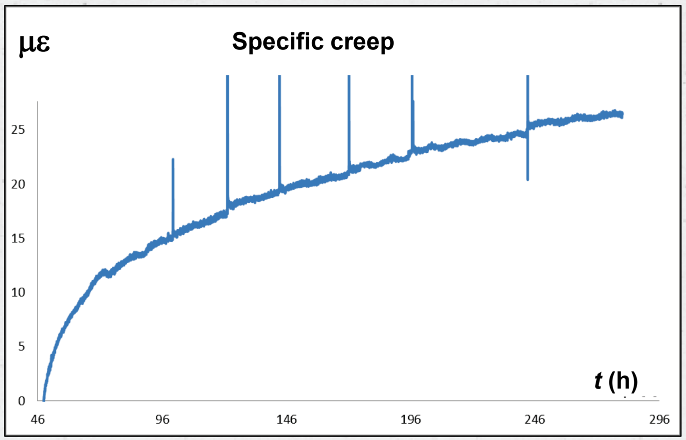
$$\varepsilon_{cc}(t) = \varepsilon_{s,sh}(t)\left(1 + \frac{E_s}{E_c(t)}\,\rho\right) - \varepsilon_{cD,sh}(t) + \varepsilon_{s,\Delta T}(t)\left(1 + \frac{E_s}{E_c(t)}\,\rho\right) - $$
$$-(\alpha_c - \alpha_s)\Delta T(t) + \varepsilon_{s,N}(t)\left(1 + \frac{E_s}{E_c(t)}\,\rho\right) - \frac{N(t)}{E_c(t)\,A_c} - \varepsilon_{c,a}(t)$$

Some results from the VRF



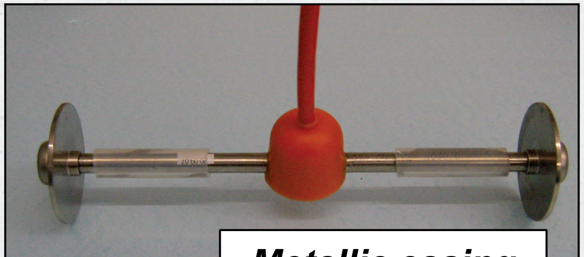


- It also allows assessment of the $E_c(t)$ evolution (via short duration unloading/reloading cycles performed along the test).
- The VRF works even if the restrained concrete specimen cracks.

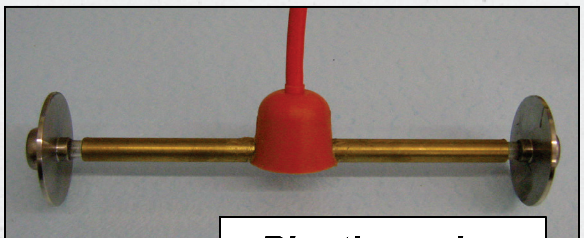


Sensors for monitoring T and strains

Vibrating Wire Strain Gages - T and ε_c



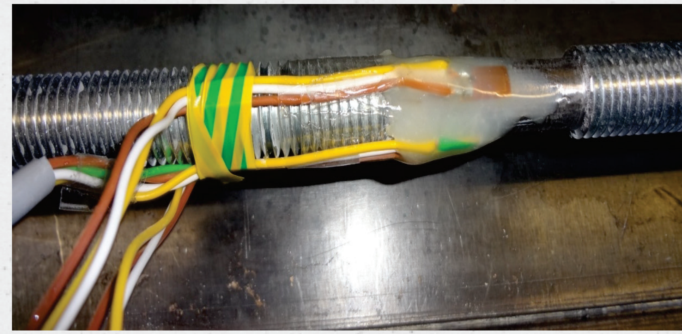
Metallic casing



Plastic casing

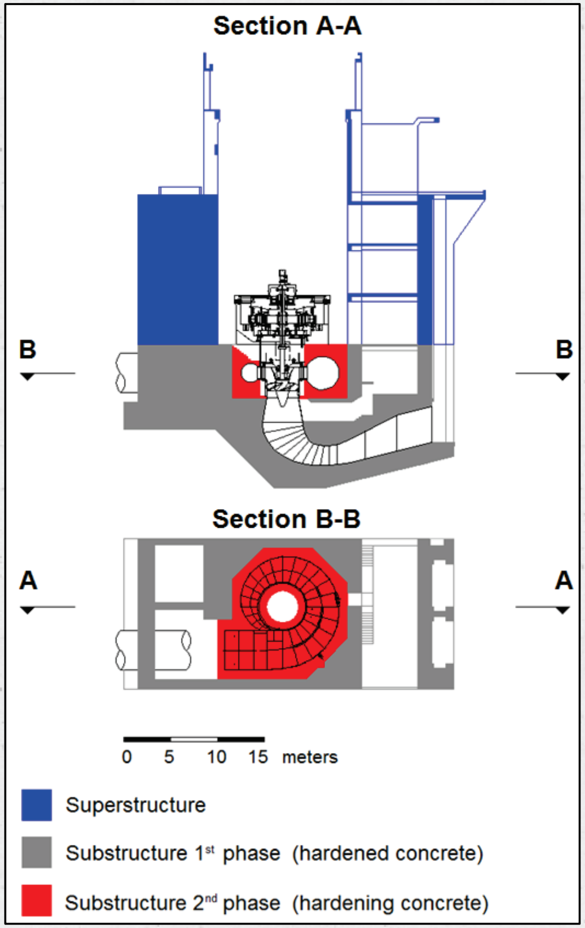
PT100 thermal sensors - T

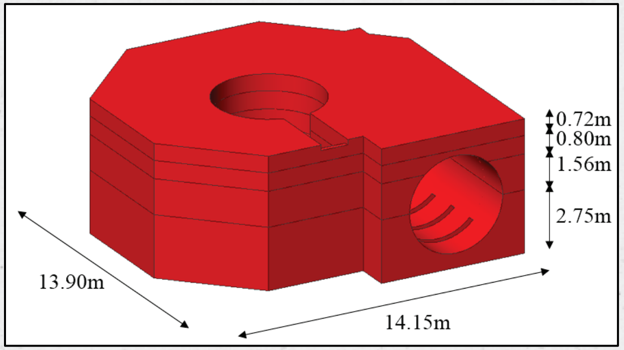
Electrical strain gages - ε_s



Carlson sensors - T and ε_c (dams)

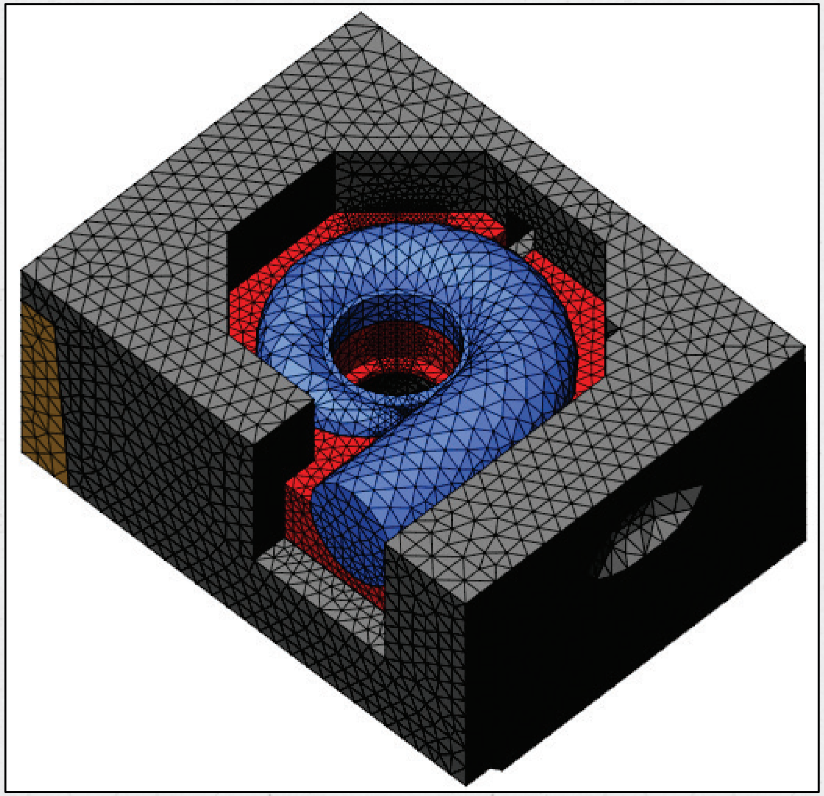
Case study

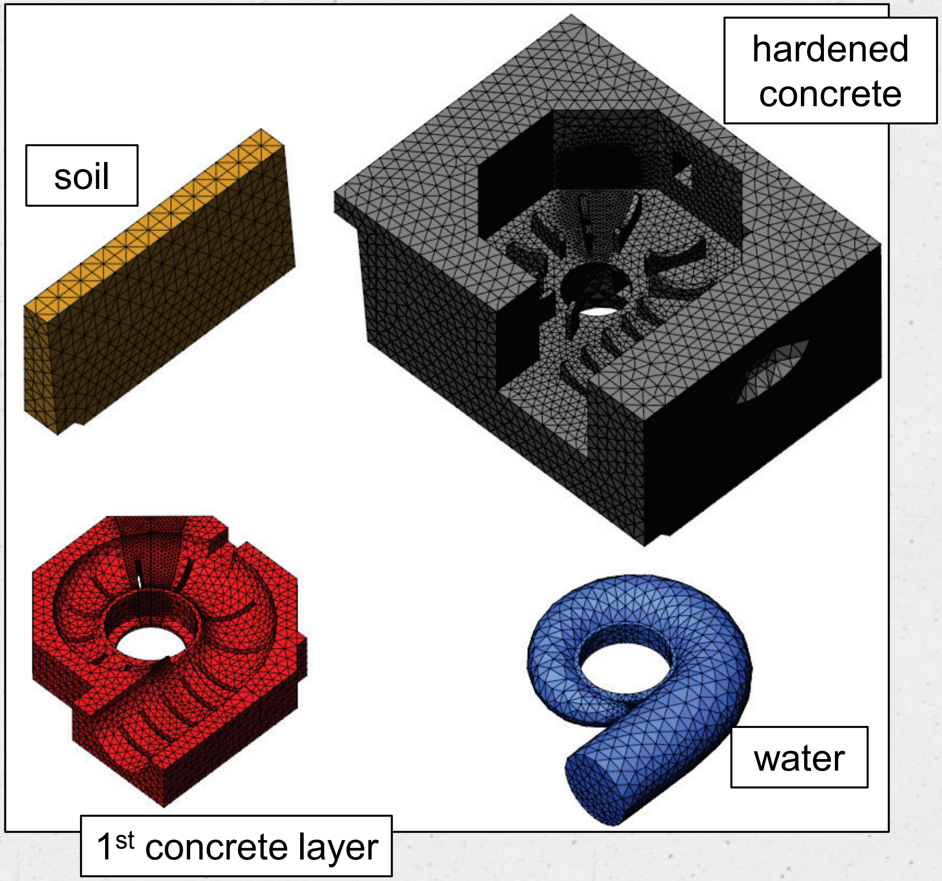




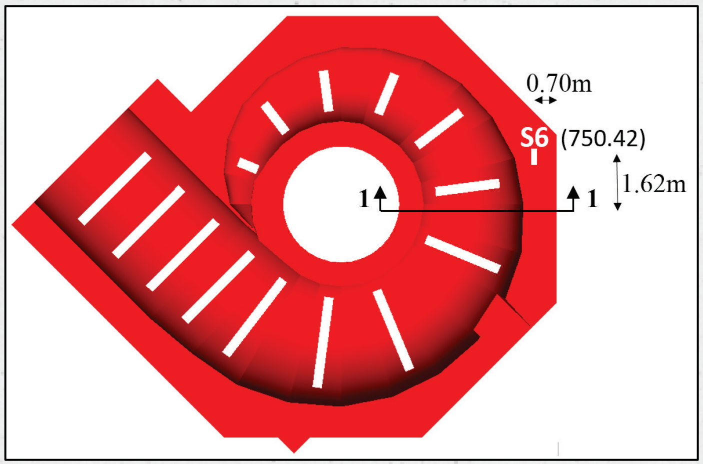
- Concrete embodying the Turbine Spiral Case of the Power Station of Batalha dam (Brazil).
- 4 concrete casting layers, with thicknesses: 2.75m, 1.56m, 0.80m and 0.72m.
- 1st layer consumes a concrete volume of 250m^3; the others ~100m^3.
- The spiral is made-up of steel and contains water under pressure during the casting operations.

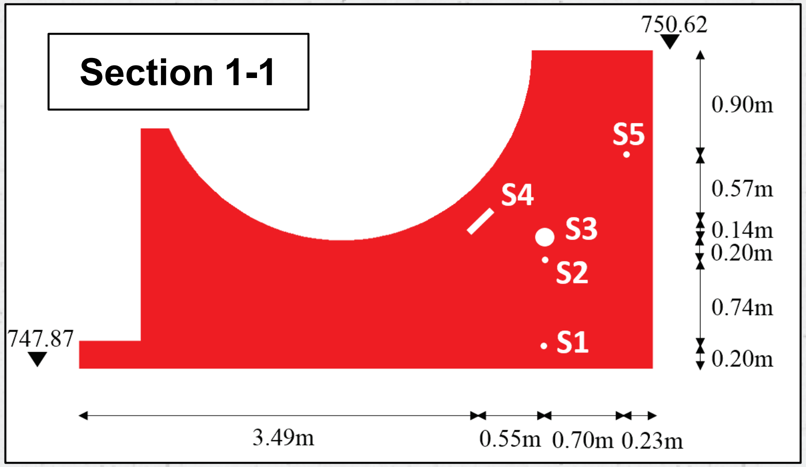
FEM model (with the 1st concrete casting layer)





Monitoring of *T* and strains

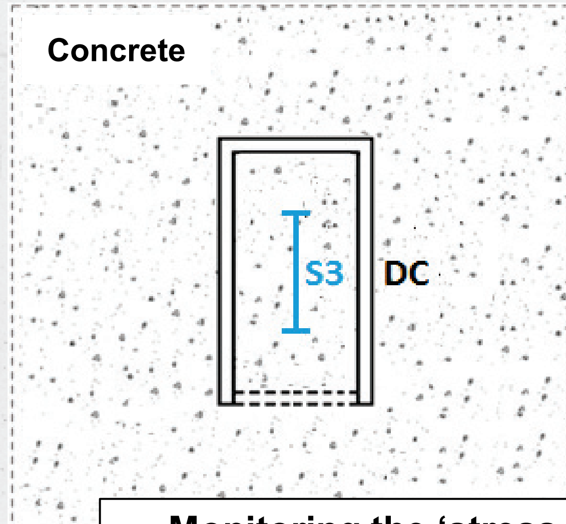




- 6 **Carlson** sensors (strains and temperatures) were installed on the 1st casting layer, mostly on Section 1-1.
- Temperatures monitored on S6 helped validation of the adopted h_{cr} coefficient.

(...)

Carlson sensors



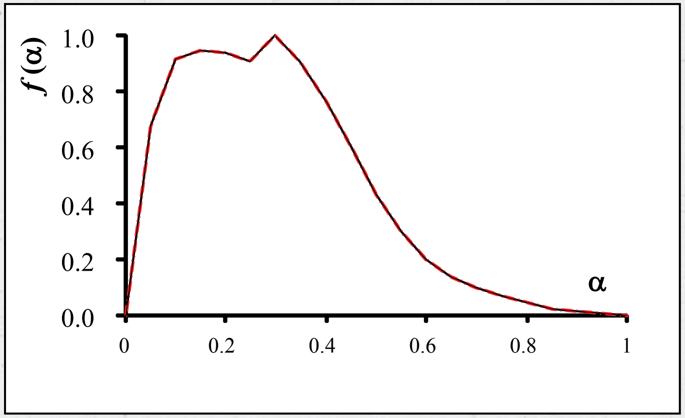
Monitoring the ‘stress-free’ concrete volumetric strains

Properties for the thermal analysis

Material	k (Wm^{-1}K^{-1})	ρc (kJm^{-3}K^{-1})
Concrete	3.0	2420
Water	0.6 ⇒ **4.0**	4187
Soil	2.87	2261

Isothermal testing	Q_∞ [kJ/kg]
15°C	269.25
25°C	274.61
35°C	288.15
45°C	293.18
55°C	317.79

Interface	h_{cr} (Wm^{-2}K^{-1})
Concrete-air	10
Concrete-formwork-air	4.3



- Initial temperature of concrete: ~32ºC.
- Average daily ambient temperature: ~25°C.

$a = 1.74994\times10^9$ W

$E_a = 3.6509$ kJmol^{-1}

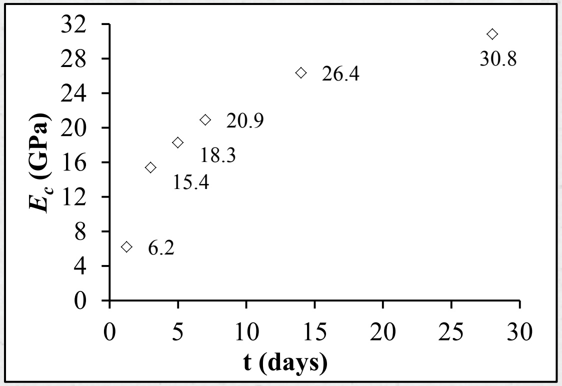
$Q_\infty = 8.6757\times10^9$ Jm^{-3}

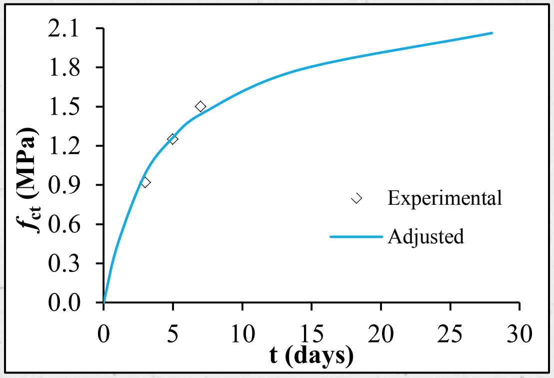
Properties for the mechanical analysis

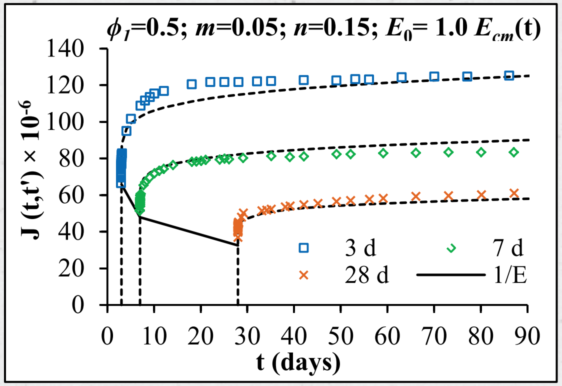
Soil: E_s = 1.1 GPa; υ_s = 0.2; α_s = 10×10^{-6} °C^{-1}

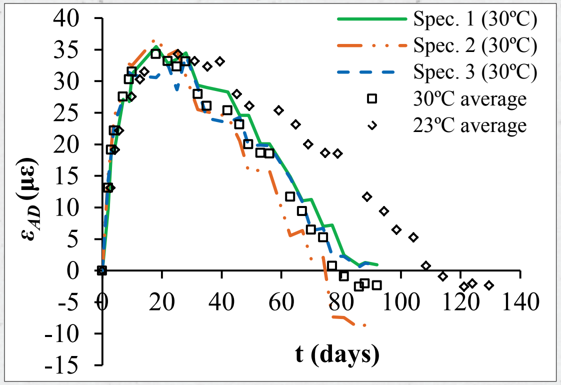
Water: K_w = 2.11 GPa; G_w = 0 GPa; α_w = 100×10^{-6} ºC^{-1}

Concrete: υ_c = 0.2; α_c =10×10^{-6} °C^{-1} (evaluated based on S3 measurements)

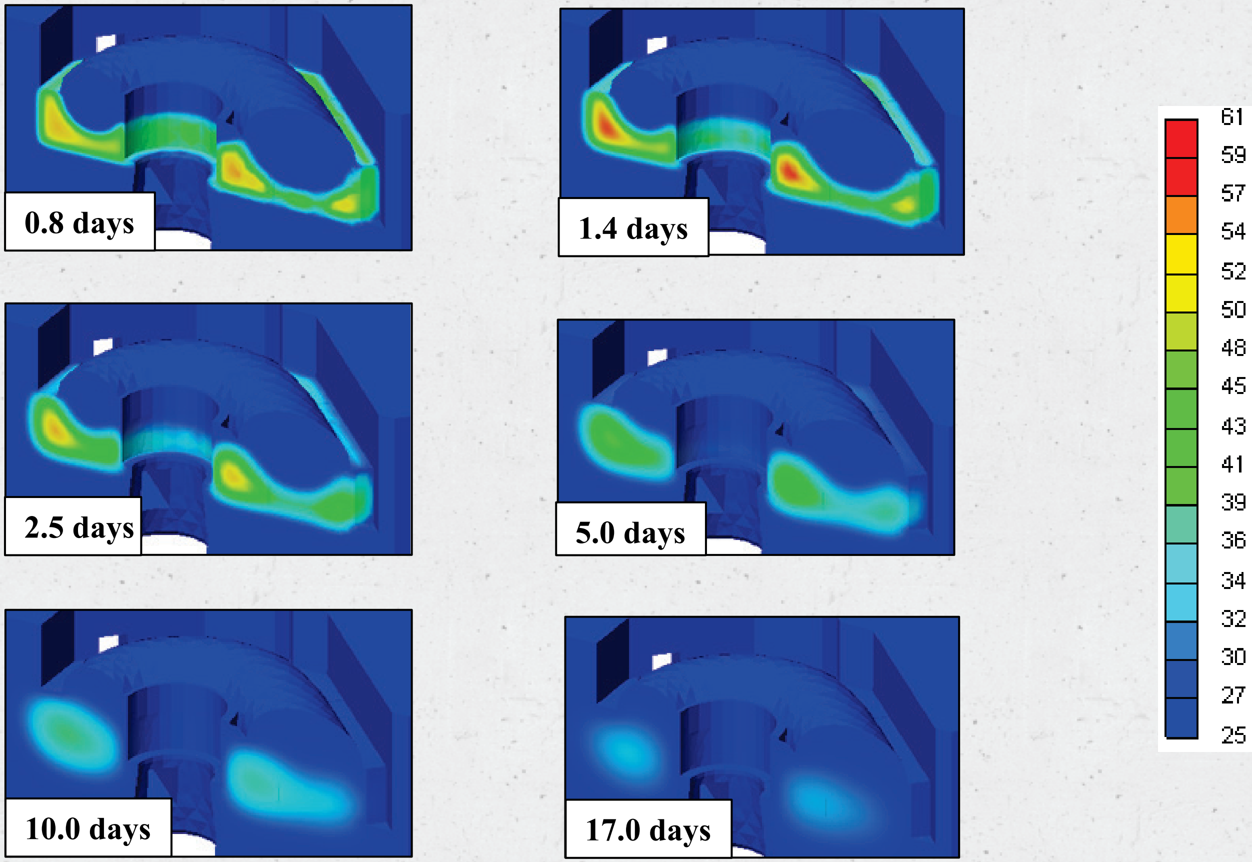




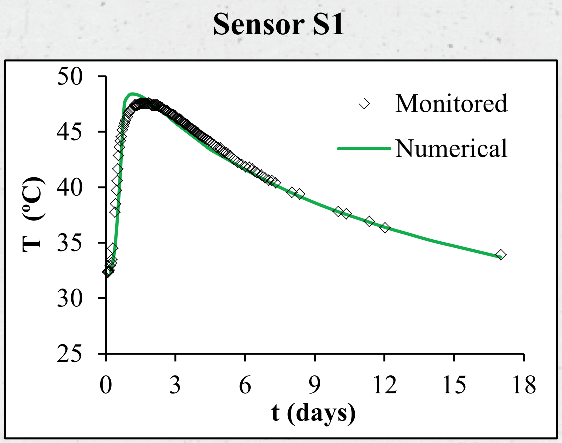


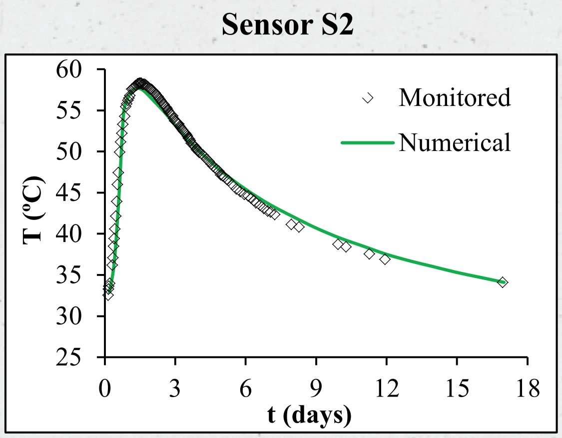


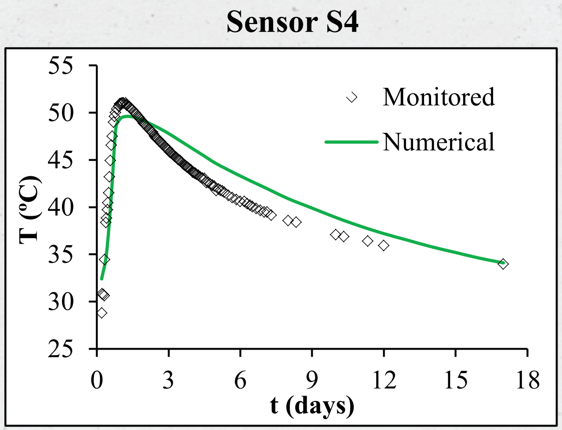
Temperatures (ºC) – Section 1-1

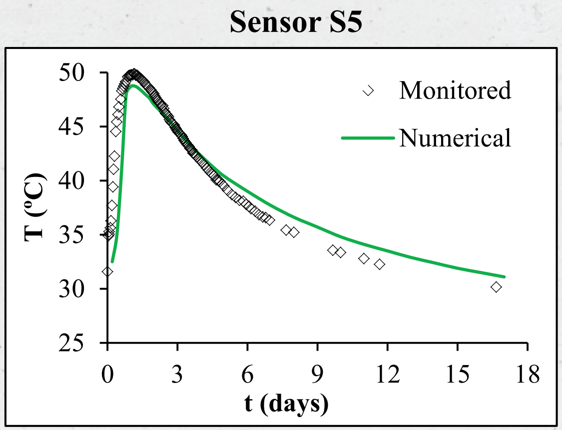


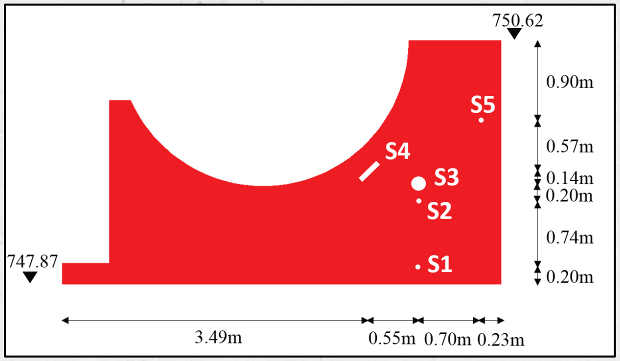
Concrete *T*: numerical *vs.* monitored



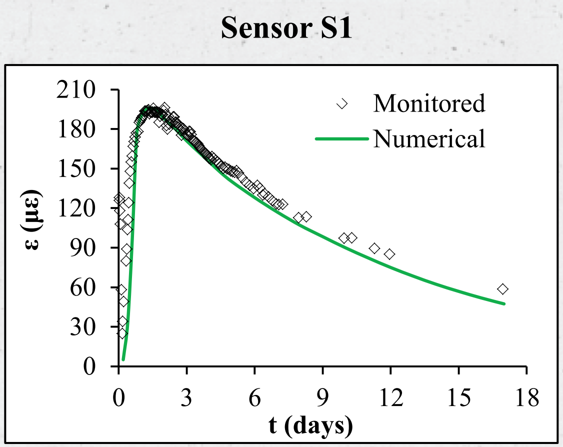


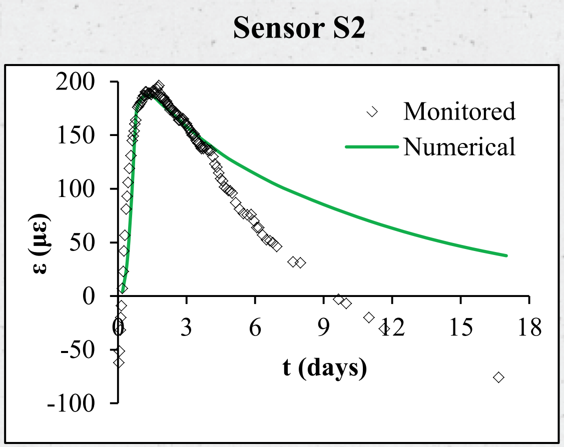


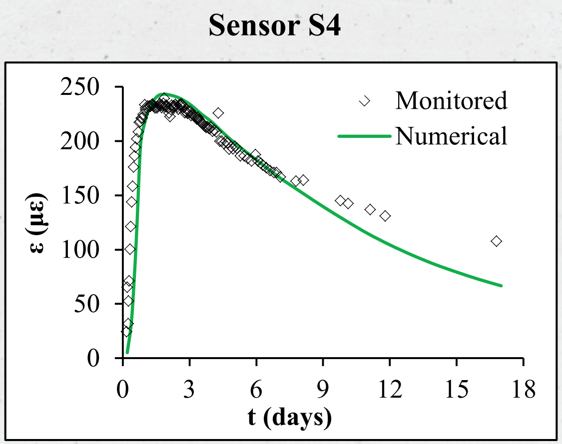


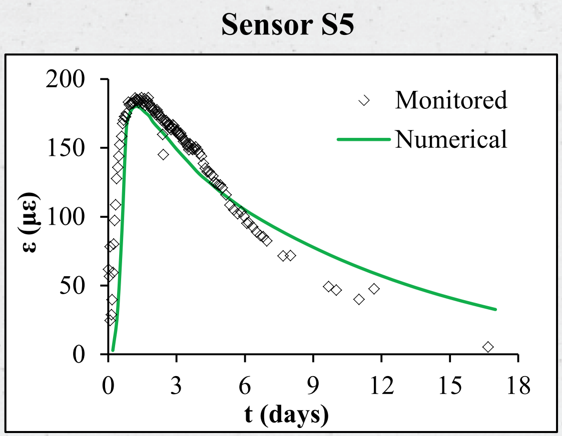


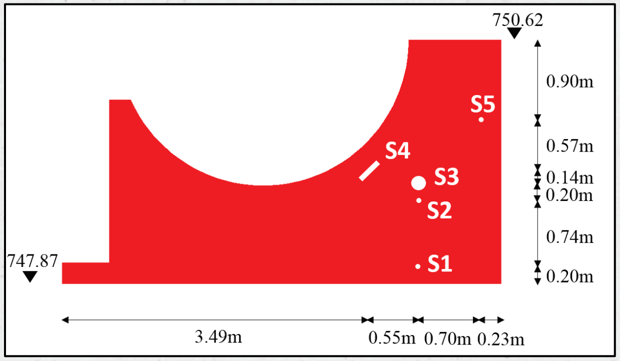
Concrete total strains: numerical *vs.* monitored











Conclusions

- Temperatures predicted numerically by the T-M model due to the cement hydration reactions were in close agreement to the ones monitored *in situ*.
- Concrete strains monitored *in situ* were fairly predicted by the numerical framework.
- Difficulties on getting good matches for the strains rely mostly on the unknown instant at which the sensors start to adequately measure concrete deformations, and in some cases on the disturbance on the local strain field introduced by the sensors themselves. *(Need for a new generation of sensors !)*
- Success of the actual numerical predictions relies moistly on:
  - Completeness of the experimental characterization of the concrete T-M properties.
  - Use of *in situ* monitoring, to assess the values of h_{cr} and other T-M boundary conditions.

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Modeling deformations of high-performance concrete with internal curing: from meso- to macro-level simulations

Mateusz Wyrzykowski – Empa, Swiss Federal Laboratories for Materials Science and Technology
Francesco Pesavento – Padua University
Dariusz Gawin – Lodz University of Technology
Pietro Lura – Empa and ETH Zurich

EMPA Materials Science & Technology

ETH Zürich

Motivation

- **High Performance Concrete (HPC)**
  - Low w/c ratio
  - High cement content
  - Silica fume

  - Fine structure of porosity
  - High stiffness and strength

  - High potential for cracking at early ages
    - Autogenous shrinkage + drying shrinkage
    - Thermal deformations

Burj Kalifa, Dubaj, 2010
source: wikipedia

Outline

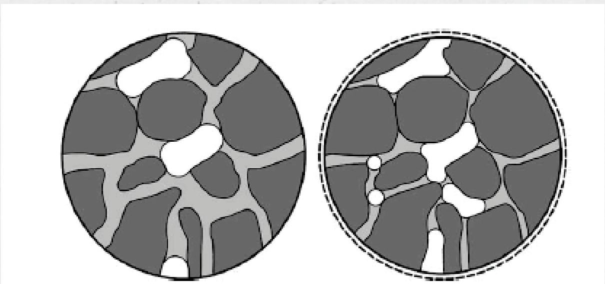
- Introduction
  - Autogenous shrinkage and drying
- Poromechanical modeling of early age concrete
  - General description of the model
  - Description of water loss and shrinkage
  - Water migration during internal curing – meso-level
  - Internal curing – macro-level
- Simulations
  - Modelling water transport during drying of HPC column
  - Effect of internal curing (high RH maintained) on thermal and shrinkge deformations

Introduction

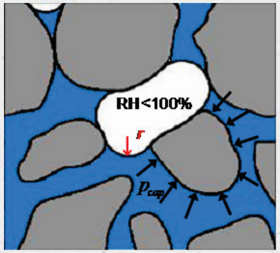
Self-desiccation and autogenous shrinkage

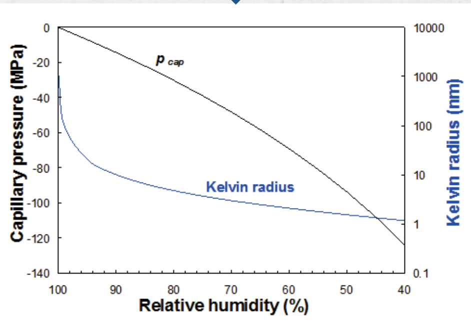
- **Self-desiccation:**
  drop of internal RH due to consumption of water in pores of decreasing dimensions (capillary effects)

- **Autogenous shrinkage:**
  bulk strain of a closed, isothermal, cementitious material system not subjected to external forces



Lura, Jensen, van Breugel, CCR 2003





Jensen and Hansen, CCR 2001
Lura, Jensen, van Breugel, CCR 2003

Introduction

Effects of moisture loss

Moisture loss

internal → **Chemical shrinkage (self-desiccation)**

external → **Loss of moisture to the environment**

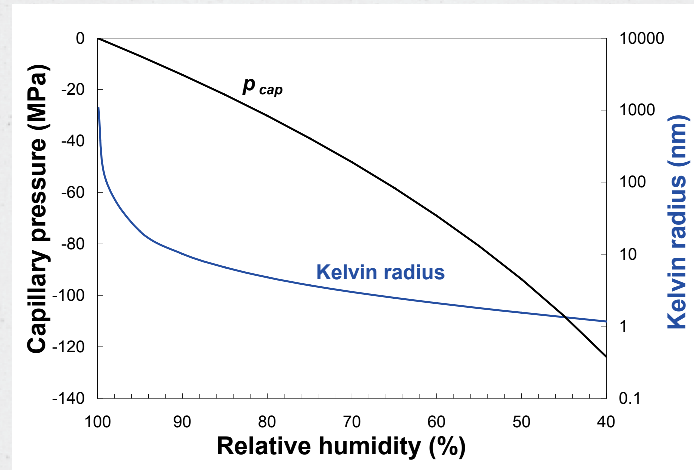
Emptying of pores

larger ➔ smaller radii

$$\ln(RH) = -\frac{2\gamma \cdot \cos\vartheta \cdot V_W}{r \cdot RT}$$

Decrease of internal RH

Shrinkage



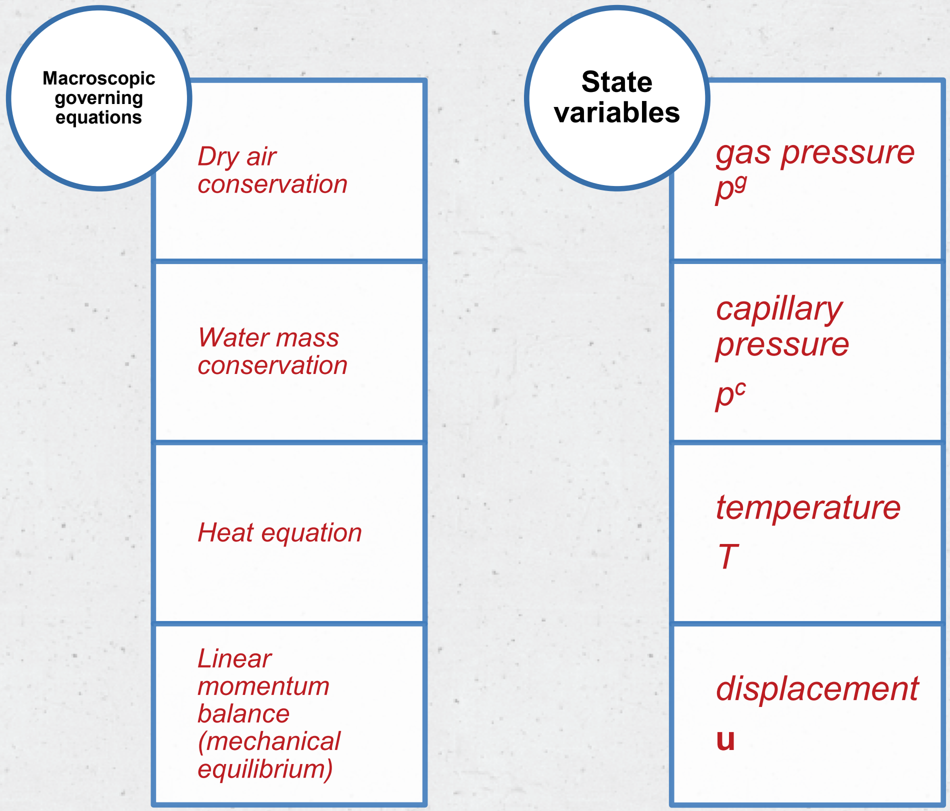
Poromechanical model
General description

- Multi-phase porous medium
  - solid (skeleton),
  - water (capillary water + bound water),
  - gaseous phase (dry air + water vapour).
- Various mechanisms of mass and energy transport
- Full coupling: hygral, thermal, chemical, mechanical phenomena

The model of concrete:
- *D. Gawin, F. Pesavento, B.A. Schrefler, Hygro-thermo-chemo-mechanical modelling of concrete … IJNME (2006)*
- *Presentation by D. Gawin*

Poromechanical model

Homogenizing scheme (overlapping continuum)



- Evolution variable: hydration degree – α (Ulm and Coussy 1995)

- *D. Gawin, F. Pesavento, B.A. Schrefler, Hygro-thermo-chemo-mechanical modelling of concrete … (2006)*
- *Presentation by D. Gawin*

Poromechanical model

Description of water loss

Water and solid skeleton mass conservation

$$n\left(\rho^{w}-\rho^{gw}\right)\frac{\partial S_w}{\partial p^c}\frac{\partial p^c}{\partial t}-\left\{\beta_s\rho^{gw}(1-n)(1-S_w)+[(1-n)\beta_s+n\beta_w]\rho^w S_w\right\}\frac{\partial T}{\partial t}+(1-S_w)n\left(\frac{\partial \rho^{gw}}{\partial T}\frac{\partial T}{\partial t}\right)+$$

$$+\left[\rho^{gw}(1-S_w)+\rho^w S_w\right]div\frac{\partial \mathbf{u}}{\partial t}-div\left[\rho^g\frac{M_a M_w}{M_g^2}\mathbf{D}_d^{gw}grad\left(\frac{p^{gw}}{p^g}\right)\right]+div\left[\rho^{gw}\frac{k\mathbf{I}k^{rg}}{\mu^g}\left(-grad\ p^g\right)\right]+$$

$$+div\left[\rho^w\frac{k\mathbf{I}k^{rw}}{\mu^w}\left(-grad\ p^g+grad\ p^c\right)\right]=\frac{\rho^{gw}}{\rho^s}(1-S_w)\dot{m}_{hydr}+\frac{\rho^w}{\rho^s}S_w\dot{m}_{hydr}-\dot{m}_{hydr}+\dot{m}_{IC}$$

Transport and exchange through boundaries

Consumption due to hydration

Source due to internal curing

Boundary conditions:

- I type (fixed value)
- II type (fixed flux)
- III type (convective)

Poromechanical model

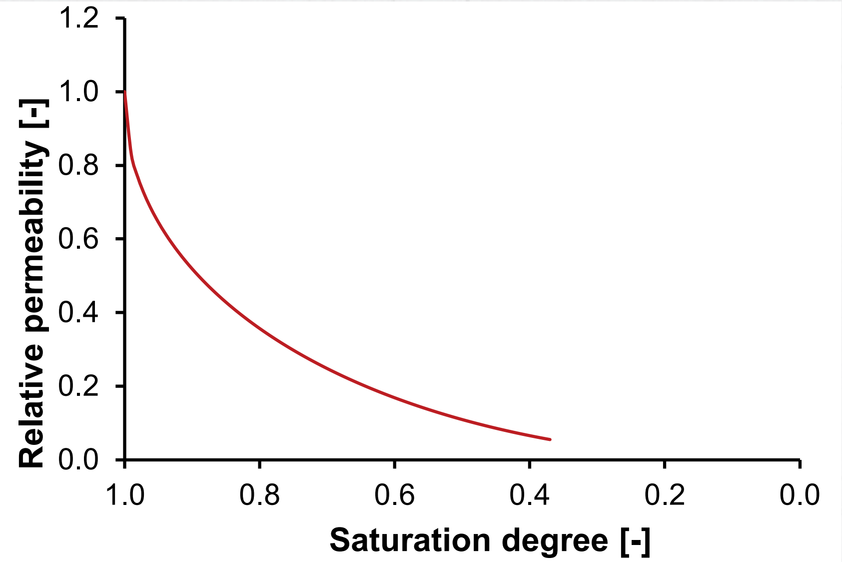
Water transport in concrete

- **Advective flow of liquid water** – Darcy's law

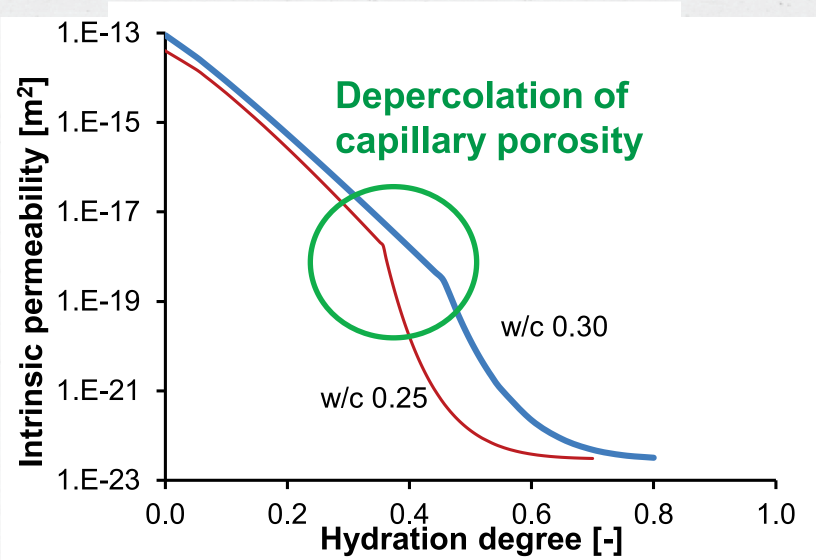
$$nS_w v^{ws} = \frac{kk^{rw}}{\mu^w}\left(-gradp^g + gradp^c\right)$$

$k(\alpha)$ - intrinsic permeability

$k^{rw}(S_w)$ – relative permeability



- *Baroghel-Bouny et al. CCR (1999)*



- *Cui and Cahyadi CCR (2001)*

- *Wyrzykowski, Lura, Pesavento, Gawin: Modeling of water migration ... MTENG (2012)*

Poromechanical model

Description of deformations

- Linear momentum balance

$$div(\dot{\sigma}) = 0$$

$$\sigma_e = \sigma + \alpha\left(p^g - Sp^c\right)$$

Gray and Schrefler
Eur J Mech A 2001

External **load** | ***Internal*** **load (drying or self-desiccation)**

Shrinkage

$$\varepsilon_{sh} = \frac{Sp^c}{3}\left(\frac{1}{K} - \frac{1}{K_s}\right)$$

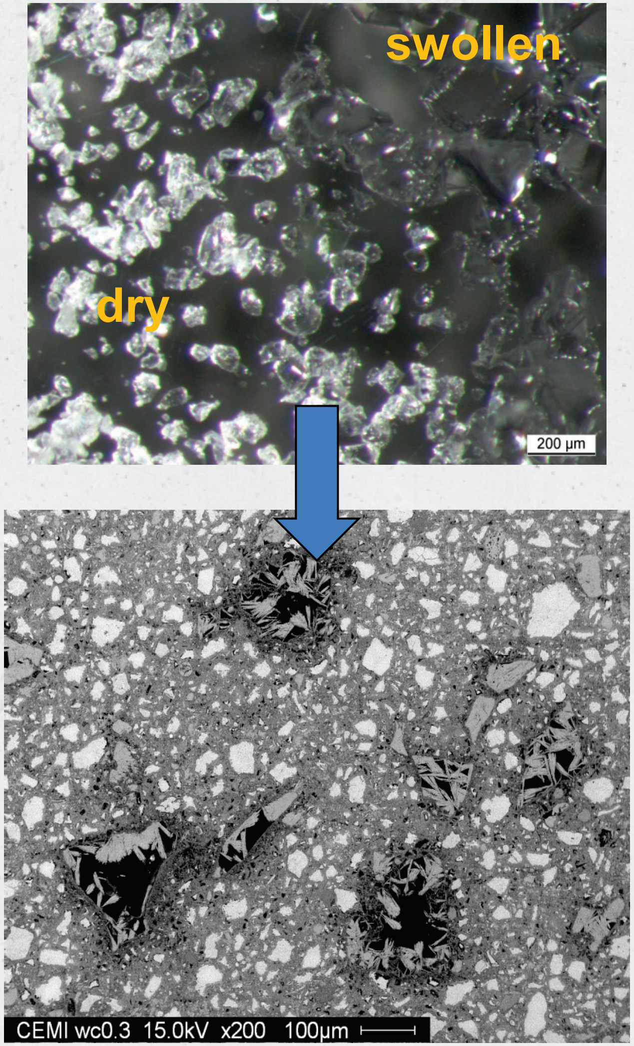
Thermal

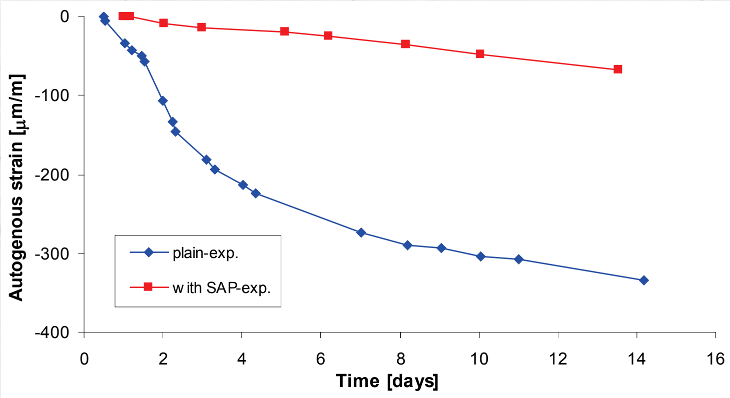
$$\varepsilon_{th} = \beta_s \Delta T$$

CTE
f(RH)

See also:
Coussy et al. 2004
Vlahinic et al. 2009

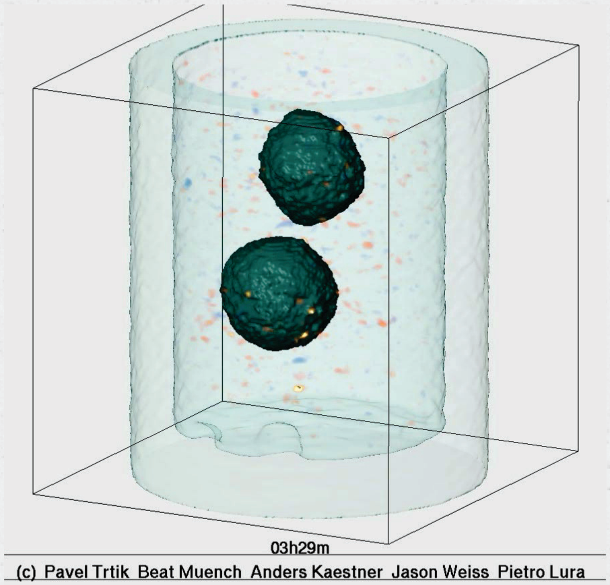
Internal curing with superabsorbent polymers (SAP)



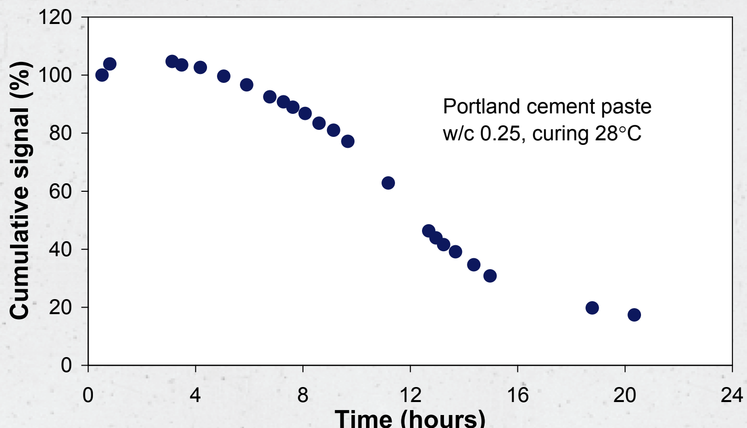


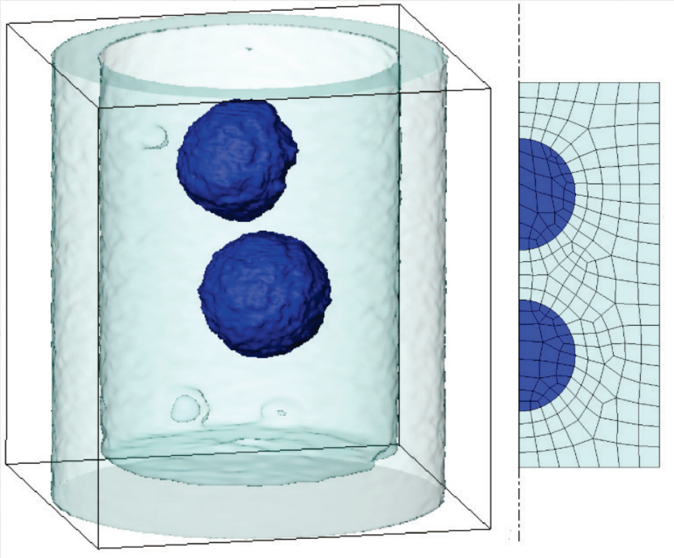
See: Jensen & Hansen** CCR **(2001, 2002)

Modelling internal curing at the meso-level



- **When is the water released from the SAP?**
- **How far does water reach in the hardening cement paste?**

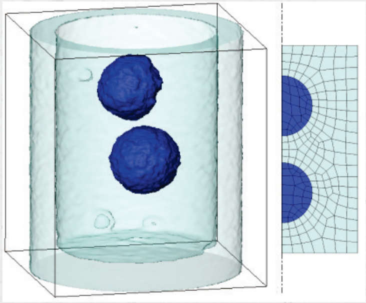


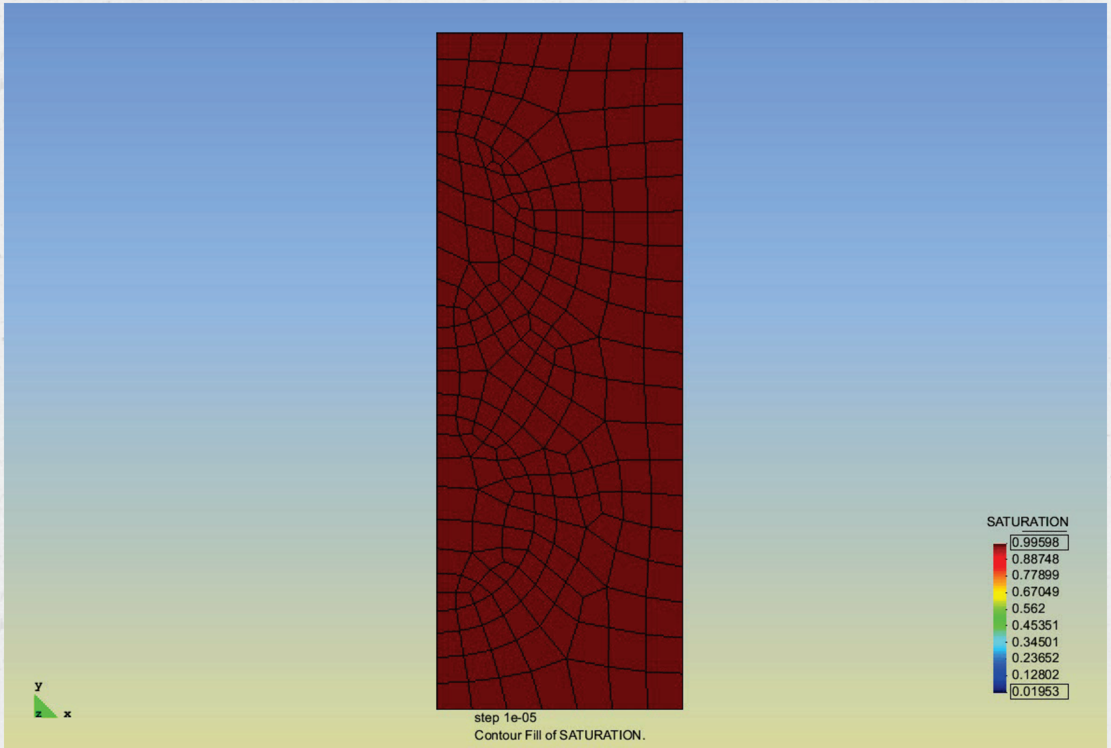


Cement paste
w/c 0.25, 6% of entrained water (vol.)

- ***Trtik, Lura et al.*** *Neutron tomography investigation of water release … 2010*

Results from the meso-level

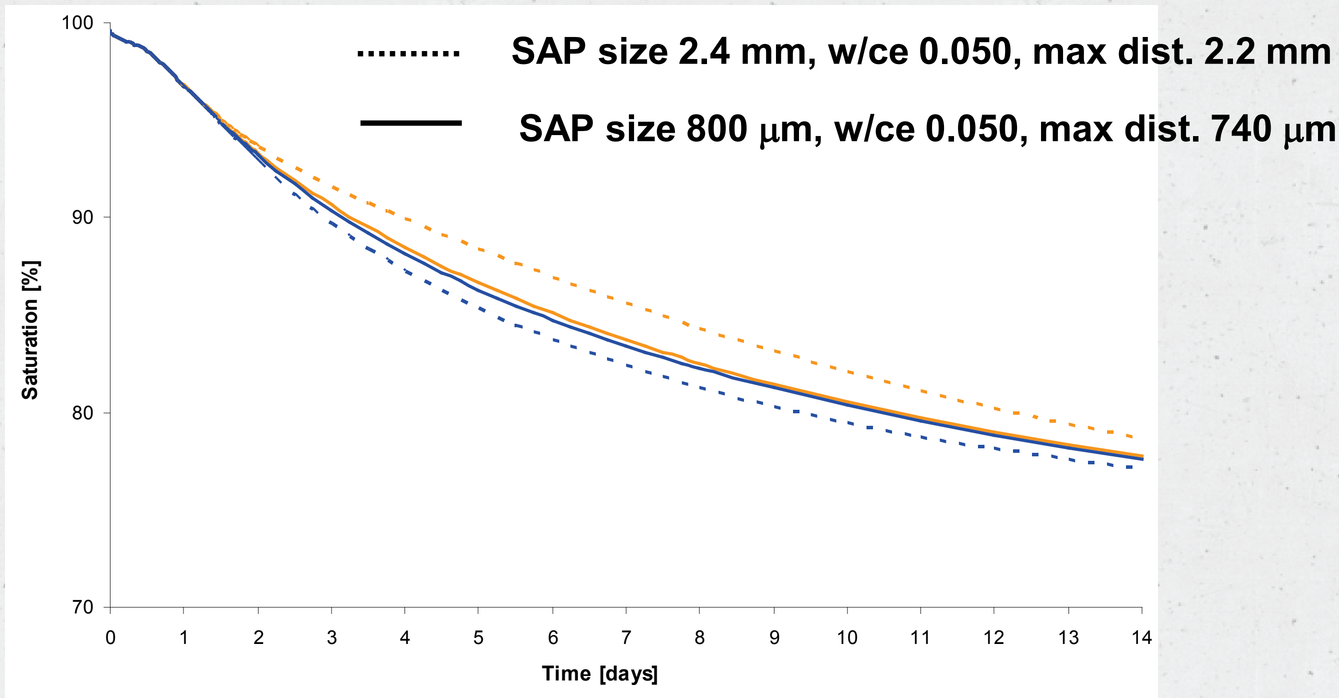


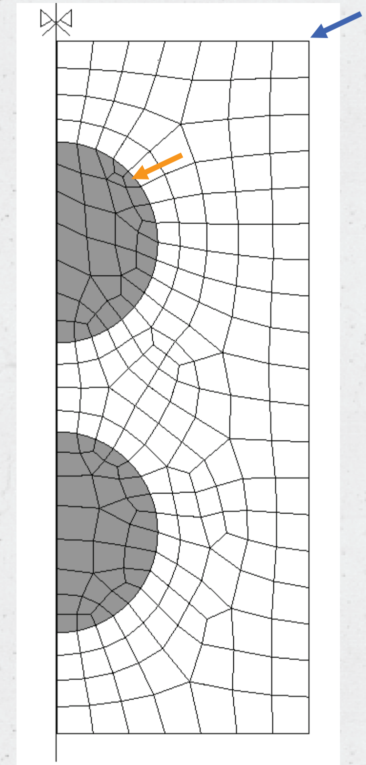


Cement paste
w/c 0.25, 6% of entrained water (vol.)

- ***Wyrzykowski, Lura, Pesavento, Gawin,*** *Modeling of water migration ... MTENG* ***(2012)***

Modelling internal curing at the meso-level





For the commonly applied sizes of SAP the whole volume of cured material is practically *uniformly and instantaneously* provided with curing water during the initial days of hydration

- ***Wyrzykowski, Lura, Pesavento, Gawin,*** *Modeling of water migration ... MTENG* ***(2012)***

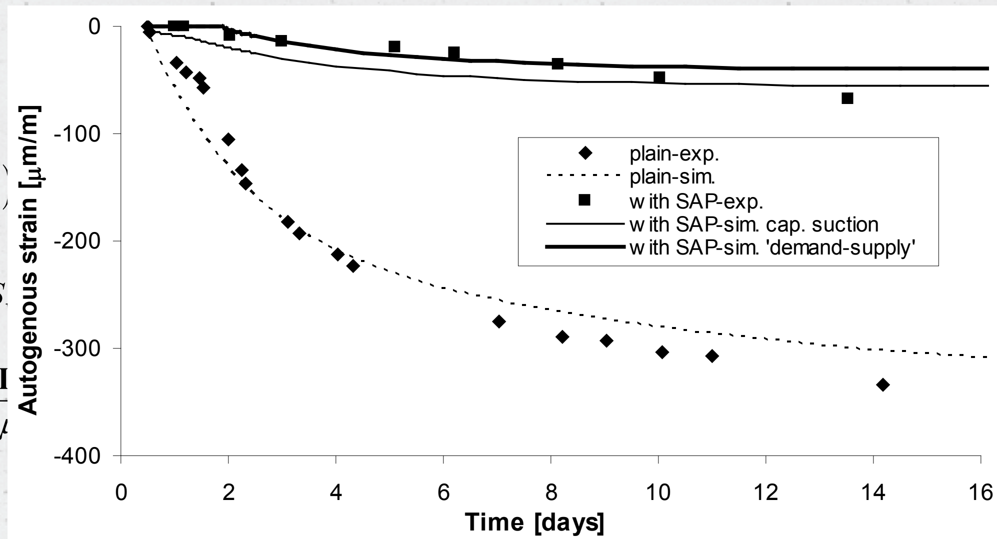
Modelling internal curing at the macro-level

Water

$n(\rho^w - \rho^{gw})$

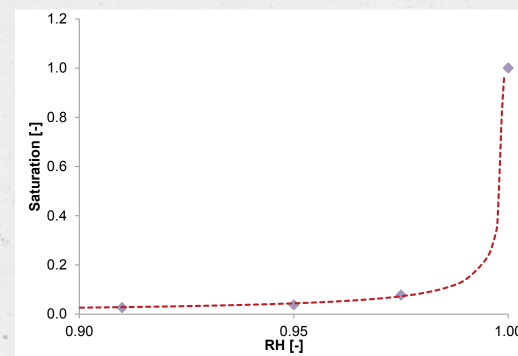
$+[\rho^{gw}(1-S$

$+div[\rho^w \frac{k\mathbf{I}}{\mu}$



$$\dot{m}_{IC}(p^c) = \frac{\eta}{1-\eta}\rho^w \frac{\partial S_w^{IC}}{\partial p^c}\frac{\partial p^c}{\partial t}$$

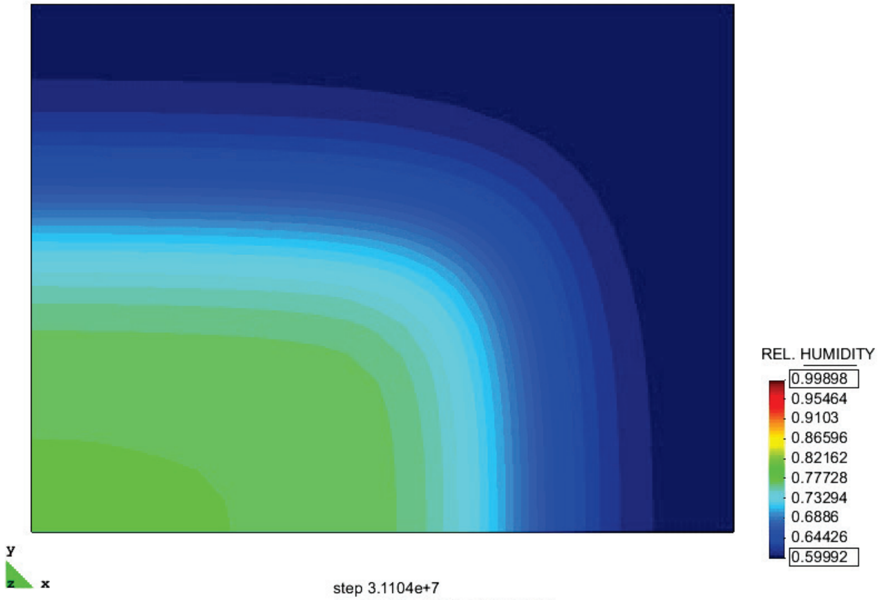
Described based on sorption isotherm of SAP



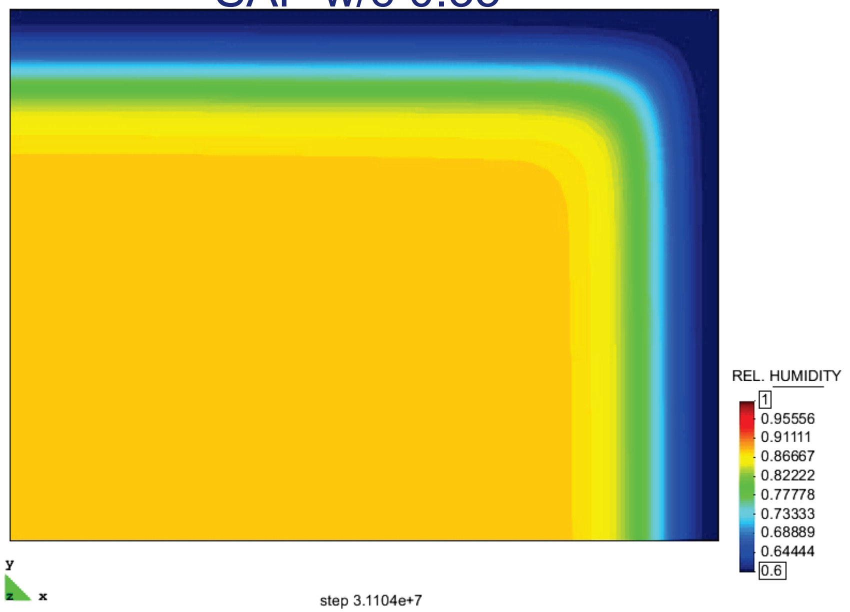
- ***Wyrzykowski, Lura, Pesavento, Gawin,*** *Modeling of internal curing in maturing mortar, CCR* ***(2011)***

Example
Drying in column cross-section

reference w/c 0.30

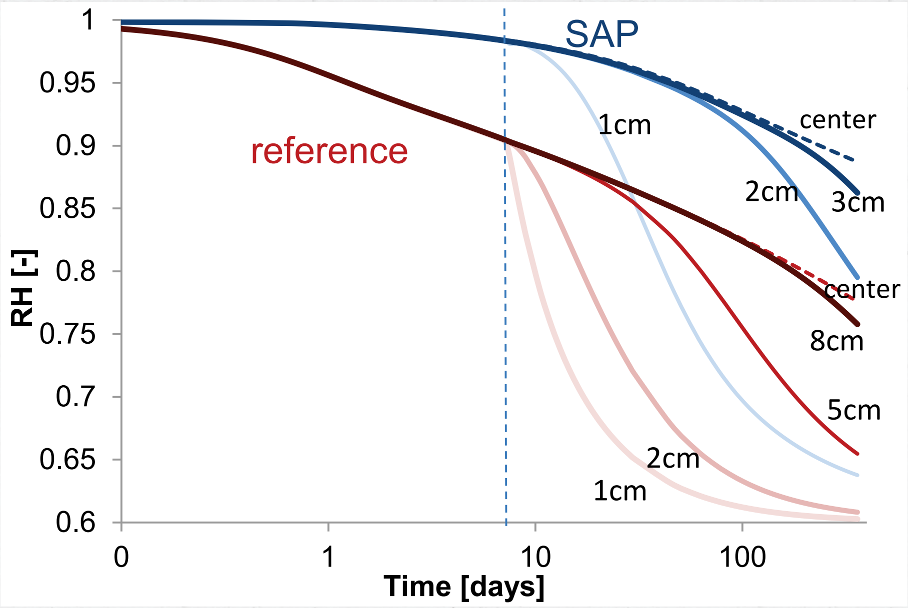


SAP w/c 0.35



Example

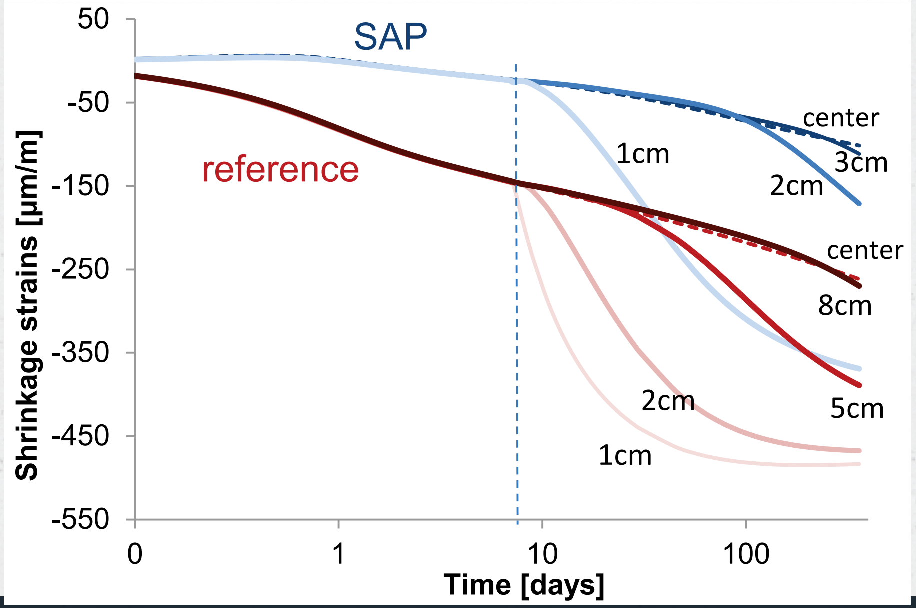
Drying in column cross-section



reference
w/c 0.30

SAP
w/c 0.35

$$\varepsilon_{sh} = \frac{Sp^c}{3}\left(\frac{1}{K} - \frac{1}{K_s}\right)$$



Summary

- The HMTRA model allows describing:
  - drying: due to self-desiccation and moisture exchange with environment
  - temperature evolution: self-heating and heat exchange with environment
  - coupled thermo-hygral behavior ➔ strains:
    - autogenous shrinkage
    - drying shrinkage
    - thermal deformations
- Evolution of material properties (transport, mechanical properties) described using hydration degreee
- Model allows describing water transport on a scale range from meso- to macro-level
- Distribution of water during internal curing can be described on a scale of single reservoirs and also on a structural level accompanying external drying

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Numerical simulation of hydro-mechanical behavior of nano-porous materials: application to cement paste

J.-B. Colliat, M. Hosseini, N. Burlion - LML, Université de Lille, France

Université de Lille 1 Sciences et Technologies

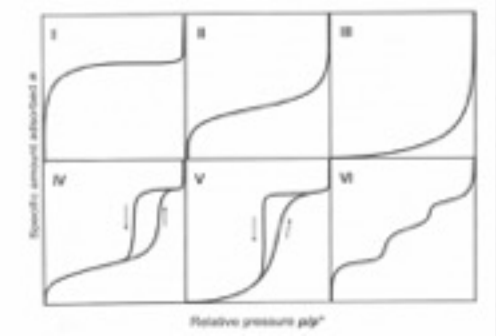
Laboratoire Mécanique Lille

CNRS

computed with Grid'5000

HYDRO-MECHANICAL BEHAVIOR

[IUPAC 1985]

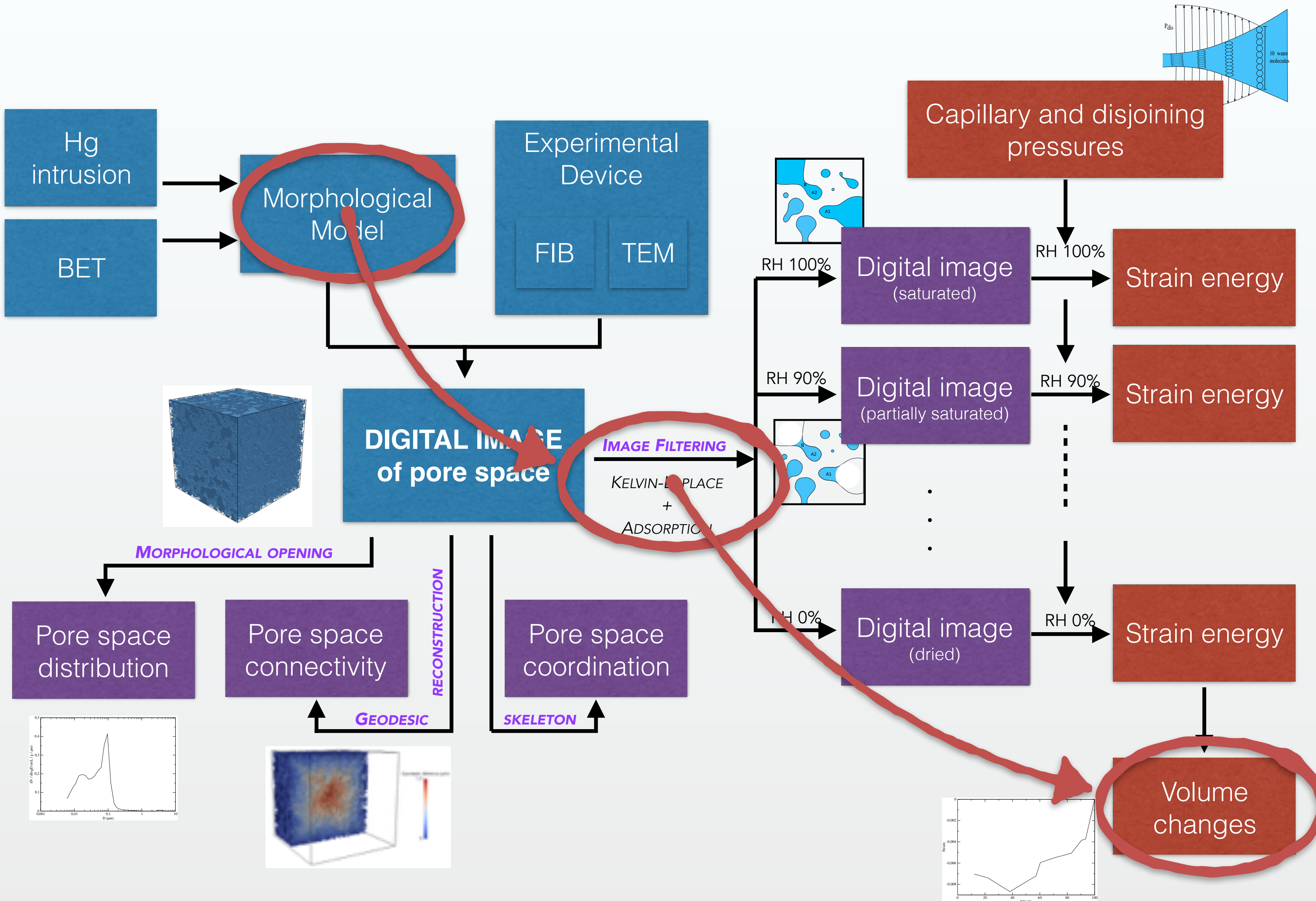


- Sorption/desorption **isotherms**
- Quite complex at macro-scale

- **Numerical simulations: Where should we put our efforts?**
  - On an accurate description of mass flows [Matheron 1976, Ahrenholz *et al.* 2008, Adler *et al.* 2005, Vennat *et al.* 2010]
  - On an accurate description of the pore space geometry [Bentz *et al.* 1998, Hilpert *et al.* 2003]
  - ''Mixed'' [Ranaivomanana *et al.* 2011]

Assumption:

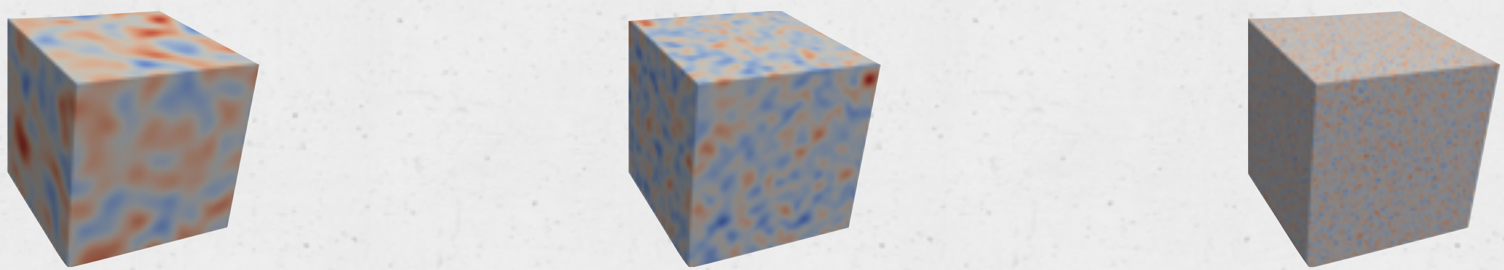
This complexity comes from the complexity of the pore space


Hg intrusion
BET
Morphological Mo del
Experimental Device
FIB
TEM
Capillary and disjoining pressures
RH 100%
Digital image (saturated)
RH 100%
Strain energy
RH 90%
Digital image (partially saturated)
RH 90%
Strain energy
DIGITAL IM
of pore spa
IMAGE FILTERING
KELVIN-L PLACE
+
ADSORPTIO
MORPHOLOGICAL OPENING
RECONSTRUCTION
Pore space distribution
Pore space connectivity
Pore space coordination
GEODESIC
SKELETON
H 0%
Digital image (dried)
RH 0%
Strain energy
Volume changes

Morphological model

- Excursion sets of **Random Fields** [Adler *et al.* 1978]

$$g(\omega, \boldsymbol{x}) \;:\; \Omega \times \mathbb{R}^N \;\to\; \mathbb{R}$$



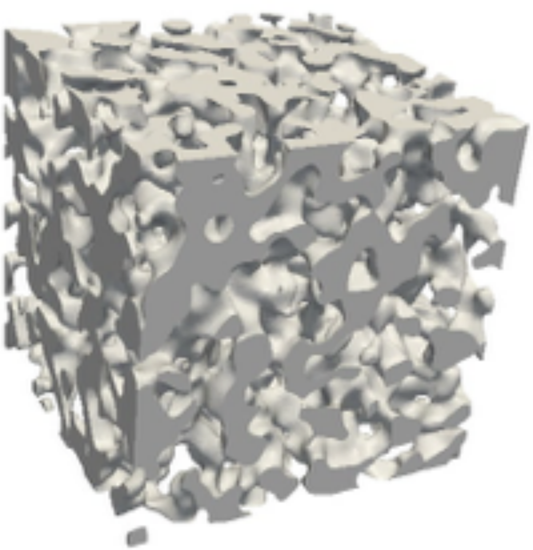
Large correlation length **Medium** correlation length **Small** correlation length

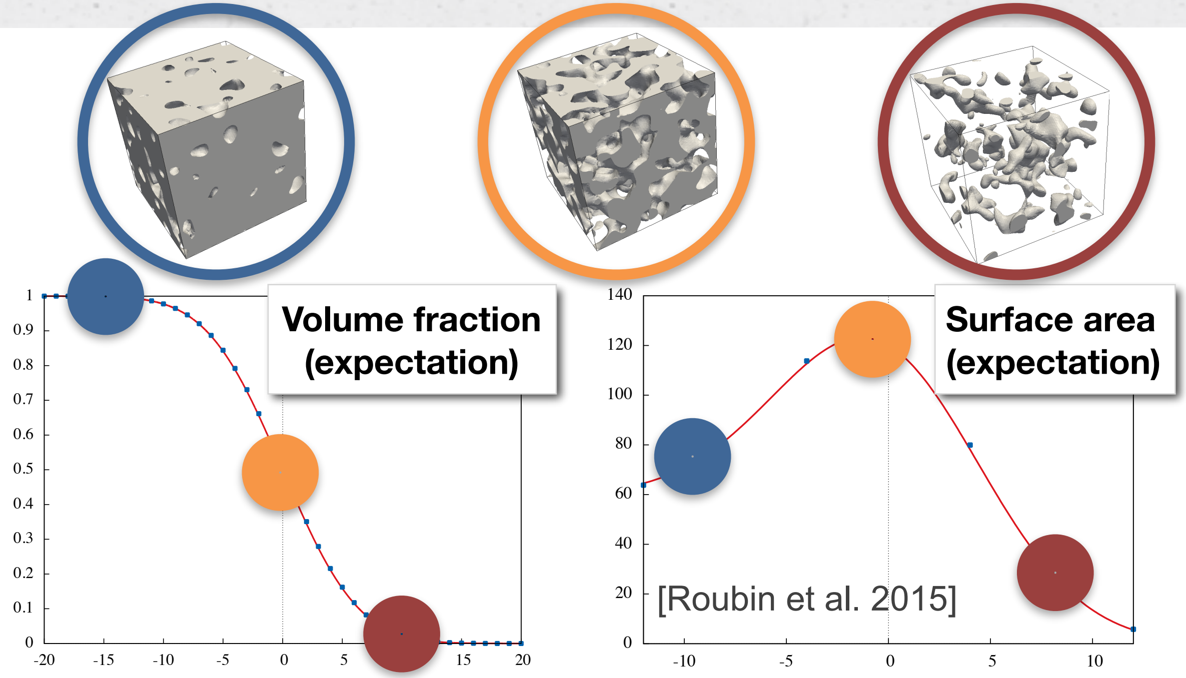
- Useful to model parametric variabilities [Keese, 2003]
- Easy simulation: ''R'' software

Morphological model

- **Excursion sets** of Random Fields [Jeulin et al. 1983, Garboczi et al. 1998, Taylor et al. 2010]

$$E_s = \{\boldsymbol{x} \in M \mid g(\boldsymbol{x}) \geq \kappa\}$$

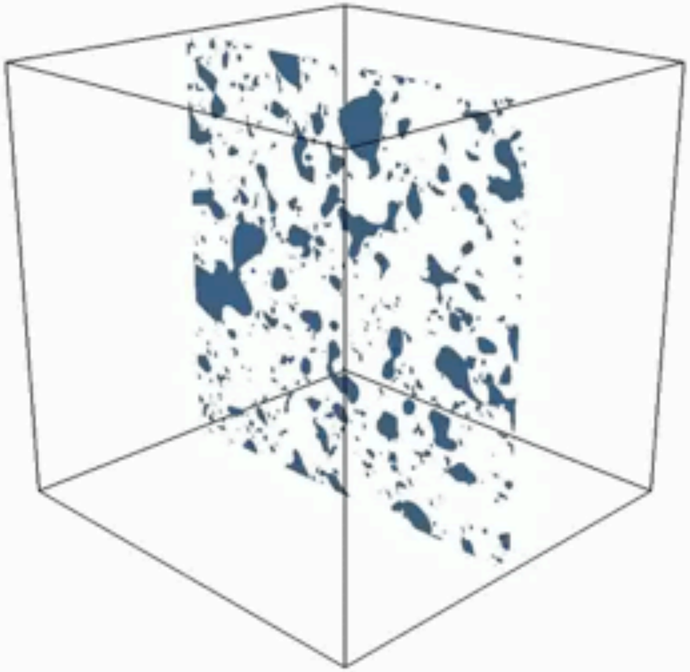




Application for a cement paste (W/C = 0.8)

1^3 micrometers^3

800^3 voxels



Targeted porosity: 31%

Targeted specific area: 31 m^2/g

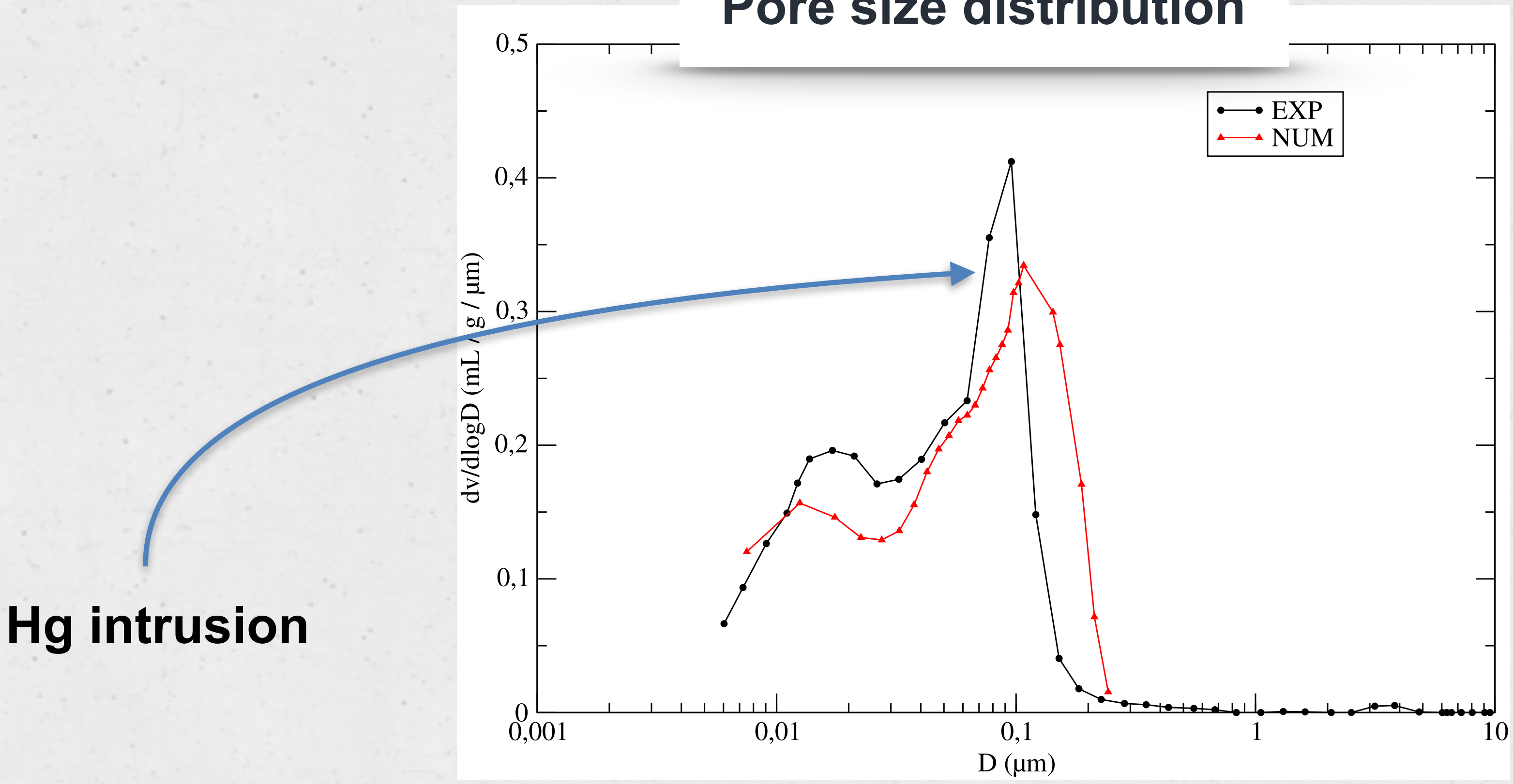
Porosity: 28.5%

Specific area: 28.8 m^2/g

Application for a cement paste (W/C = 0.8)

- Image filtering: morphological opening [Sera 1984]

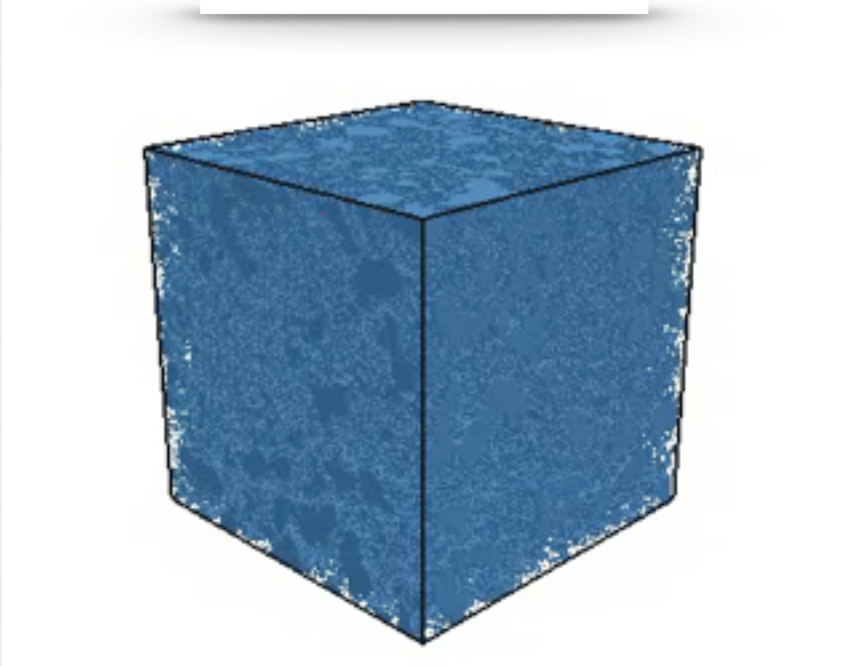
Pore size distribution



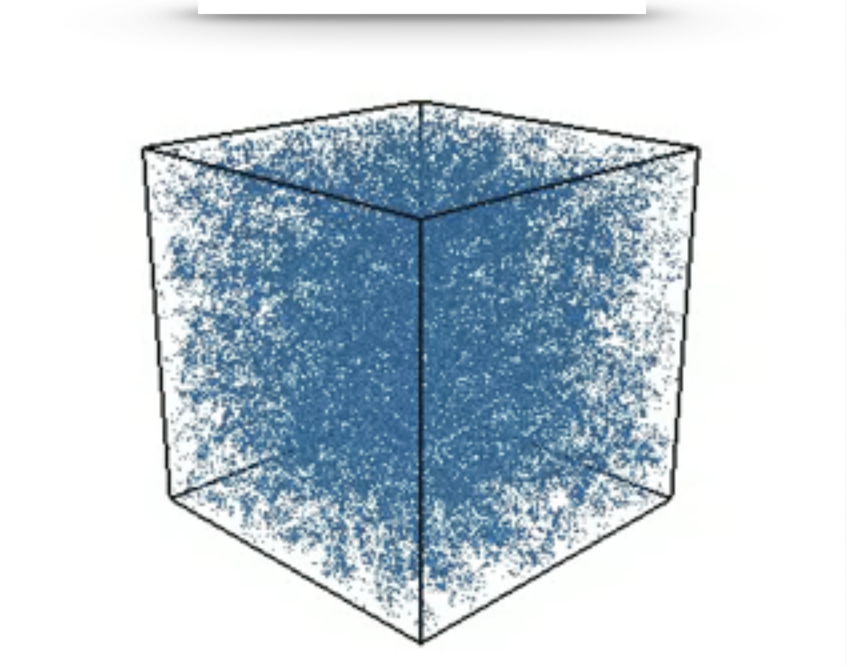
Application for a cement paste (W/C = 0.8)

- Image filtering: geodesic reconstruction [Sera 1984]

Open porosity



Closed porosity

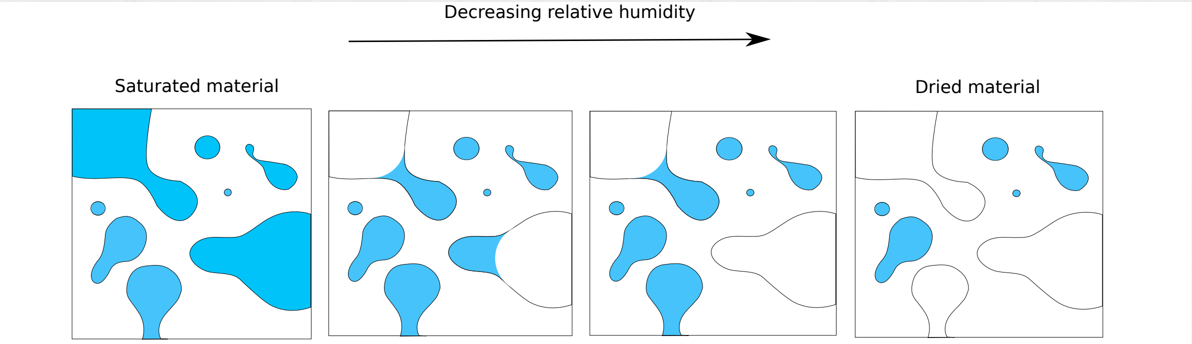


Desorption isotherm

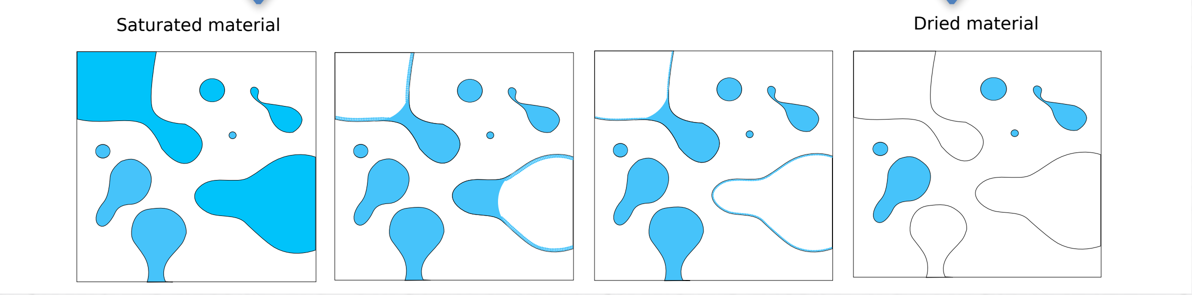
Kelvin-Laplace law ⇨

$$d = -\frac{4\gamma.M}{R.T.\rho.ln(RH)}$$

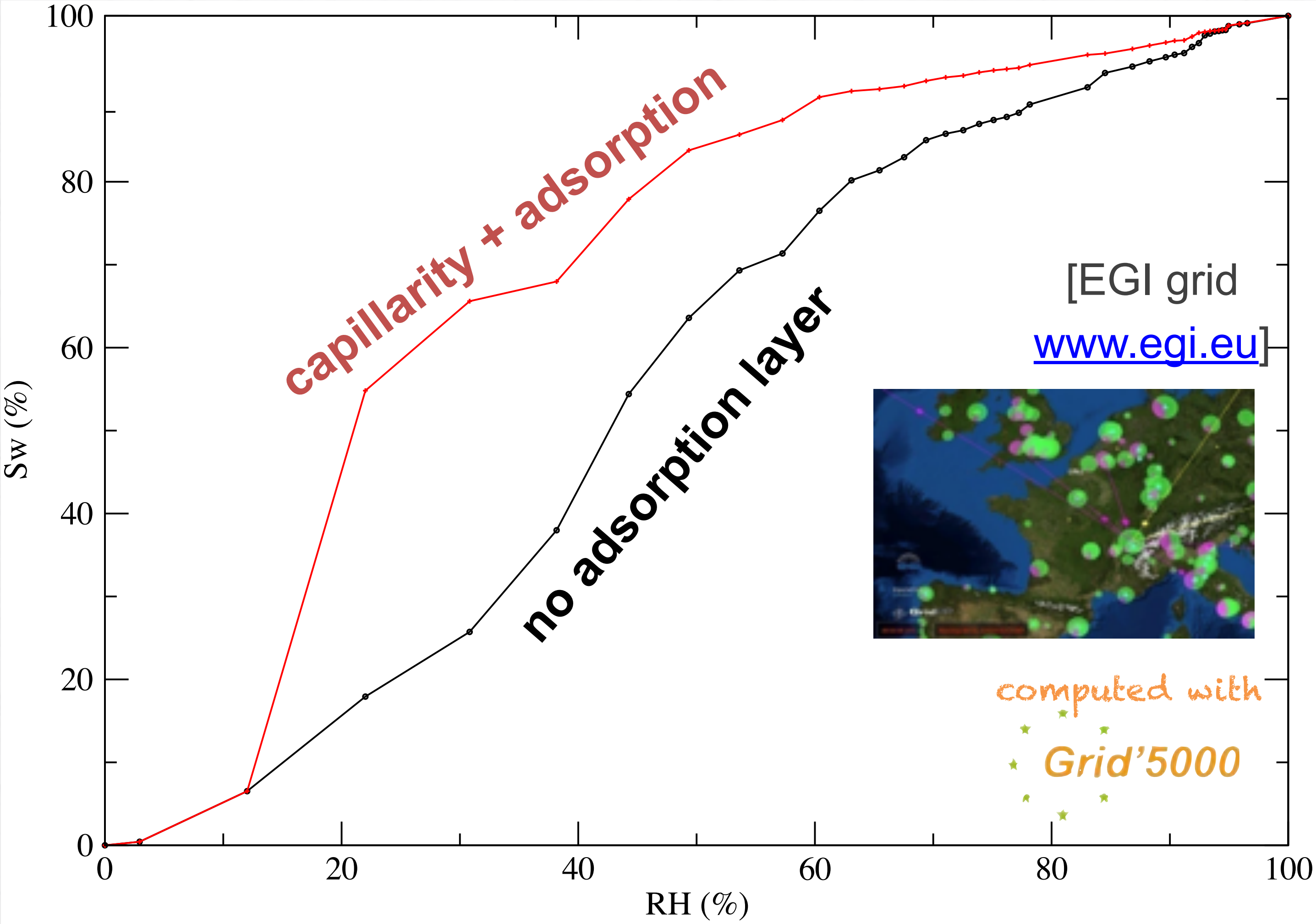
Morphological opening



Morphological erosion

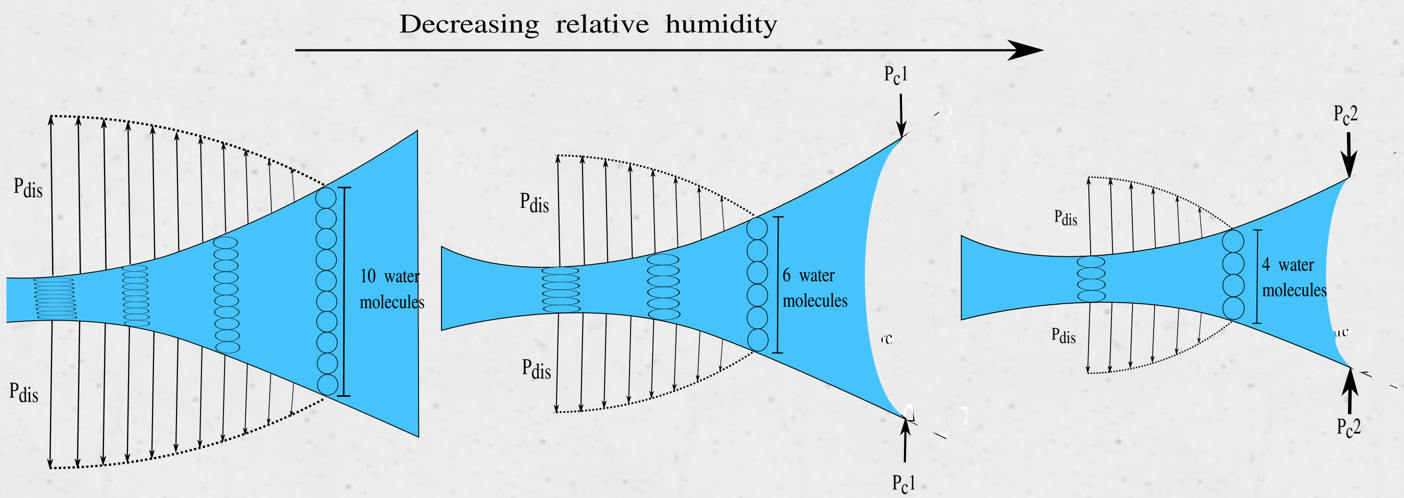


Desorption isotherm



Shrinkage

- **Capillary pressure**
- **Disjoining pressure** [*Wittmann 1968*]
- Surface energy [*Ishai 1965*]

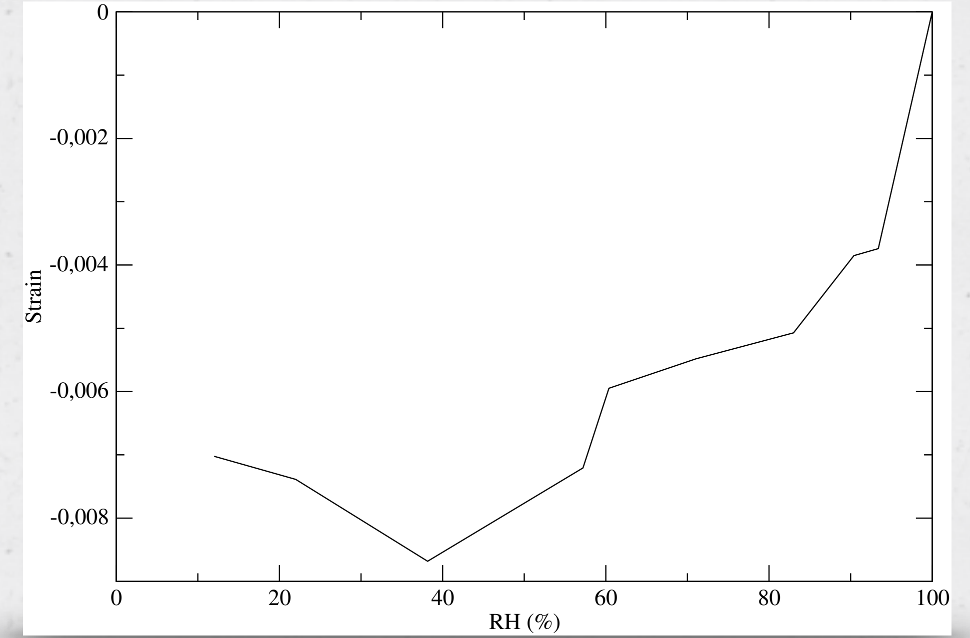


Shrinkage

- **Capillary pressure**
- **Disjoining pressure** [Wittmann *1968*]
- Surface energy [*Ishai 1965*]

- Image filtering
- Compute strain energy
  (at each RH stage)

- Higher values than expected?



Conclusions

- Assumption: the isotherms complexity inherits from the pores complexity
- Starting point: **3D digital image of pore space**

- Extracting information using image **filtering coupled to physics**:
  - for now: capillarity, adsorption
  - *working on: diffusion of vapor (kinetics)*

- Going further to **volume changes**
  - for now: capillary and disjoining pressures
  - *working on: variation of surface energy*

- More details at:

  session RS03-1, 22/Sep/2015, 4:10pm - 6:10pm, Location: H8

1404
COST ACTION

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METHODOLOGY FOR A PROBABILISTIC ANALYSIS OF AN RCC GRAVITY DAM CONSTRUCTION

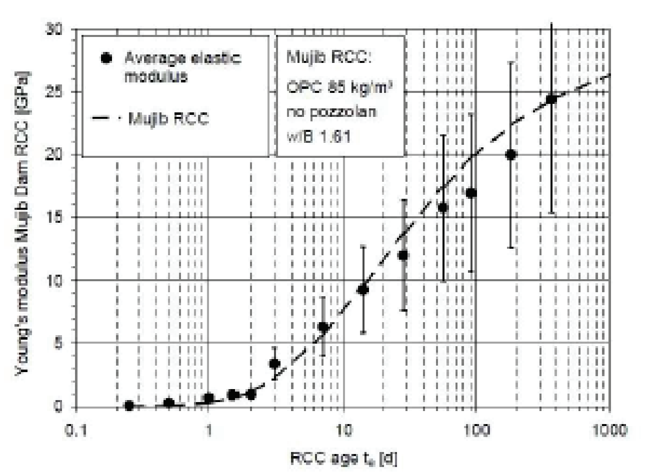
Fernando Lopez-Caballero - CentraleSupélec, France
Ana Gaspar - CentraleSupélec, France
Arezou Modaressi - CentraleSupélec, France
Antonio Gomes-Correia - Universidade do Minho, Portugal

OBJECTIVES

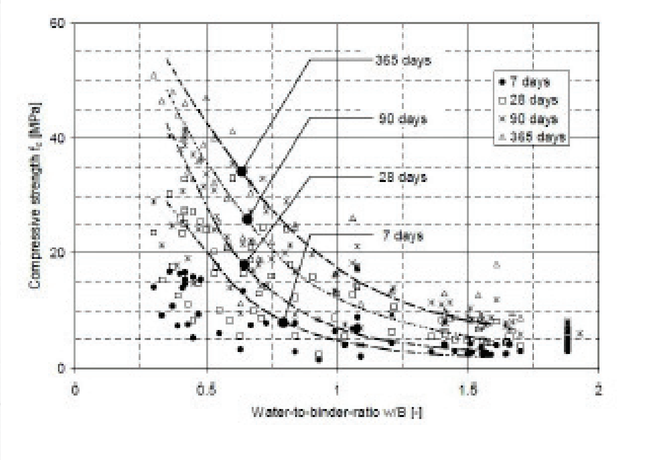
- What?
  - To assess probability of failure obtained for a certain limit-state (i.e. cracking),
  - given uncertainties related to some input parameters.
- How?
  - By coupling Finite Element Methods with Reliability Methods (i.e. Monte Carlo).
- Why?
  - Probabilistic tools are a complement to the deterministic classical tools based mostly under the basis of an empiric global security coefficient.

UNCERTAINTIES:

- ambient temperature - casting temperature;
- mechanical properties and their evolution in time;
- adiabatic heat rise;
- planned construction schedule …
- **models increasing complexity** leads to increase number of parameters that have to be determinate

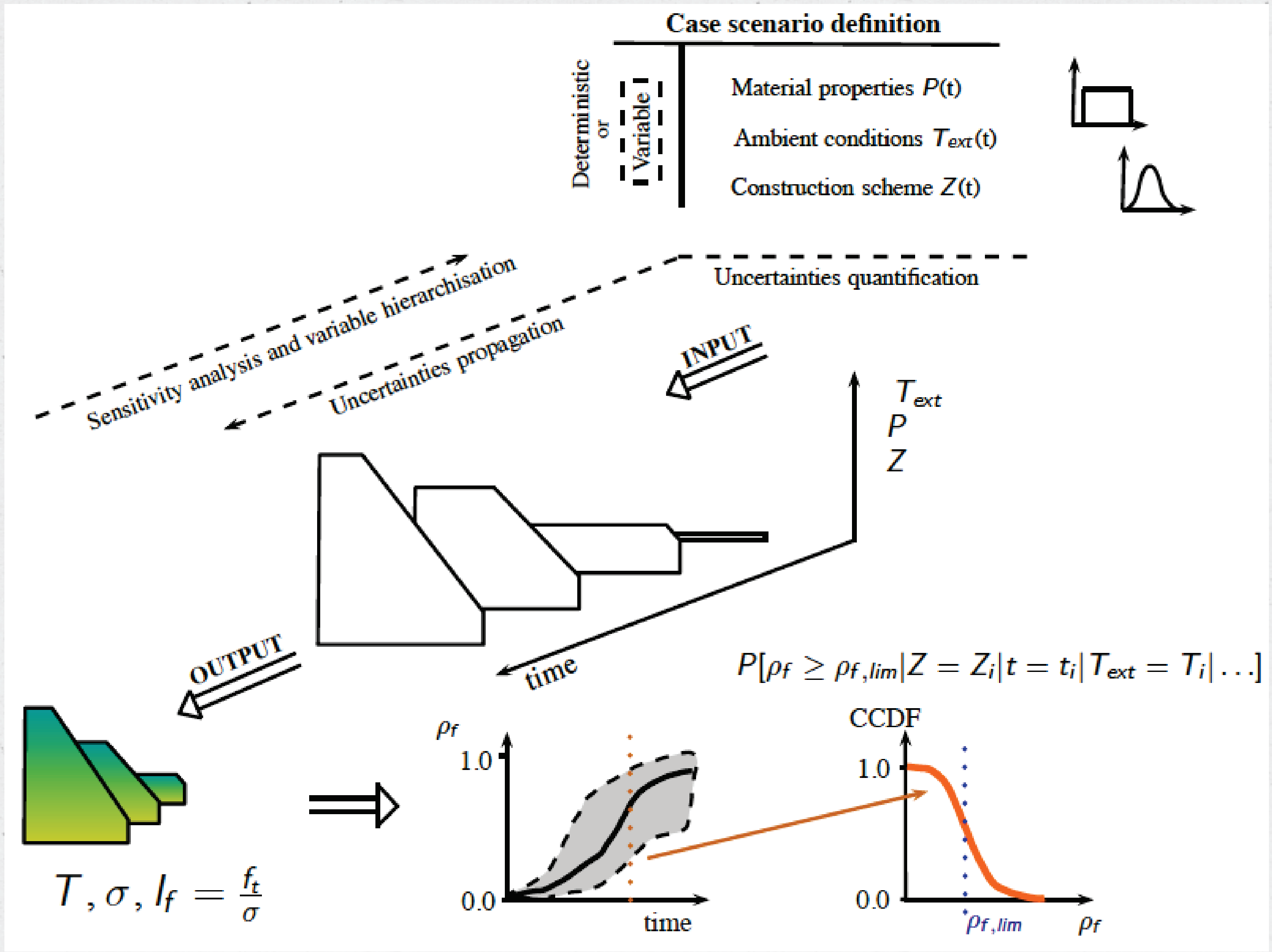


RCC Mujib Dam (Conrad, 2006)



(Conrad, 2006)

OVERVIEW OF THE WORK



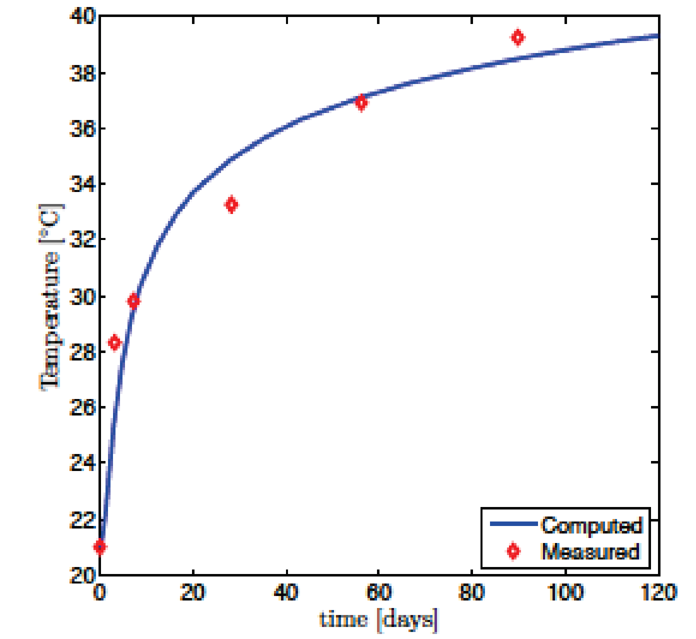
THERMO-CHEMO-MECHANICAL MODEL

- Ruled by the hydration reaction :
  - Exothermic;
  - Thermally activated.
  - Based on the theory of reactive porous media by Coussy (1996).

$$\rho \cdot c \cdot \dot{T} = -div(\underline{q}) + \dot{Q} \quad ; \quad \underline{q} = -\underline{\underline{k}} \cdot \underline{grad T}$$

$$\dot{Q} = l_\xi \cdot \dot{\xi} \quad ; \quad \dot{\xi} = \tilde{A}(\xi) \cdot \exp\left(-\frac{E_a}{R \cdot T}\right)$$

$$\tilde{A}(\xi) = \frac{k_\xi}{\eta_{\xi 0}} \left(\frac{A_{\xi 0}}{k_\xi \xi_\infty} + \xi\right) (\xi_\infty - \xi) \exp\left(-\overline{\eta} \frac{\xi}{\xi_\infty}\right)$$



THERMO-CHEMO-MECHANICAL MODEL

- Introduction of an ageing degree κ(Cervera et al. 2002)
- Mechanical properties are dependent on both the temperature and hydration degree.

$$\dot{\kappa} = \lambda_T(T) \cdot \lambda_{f_c}(\xi) \cdot \dot{\xi} \geq 0$$

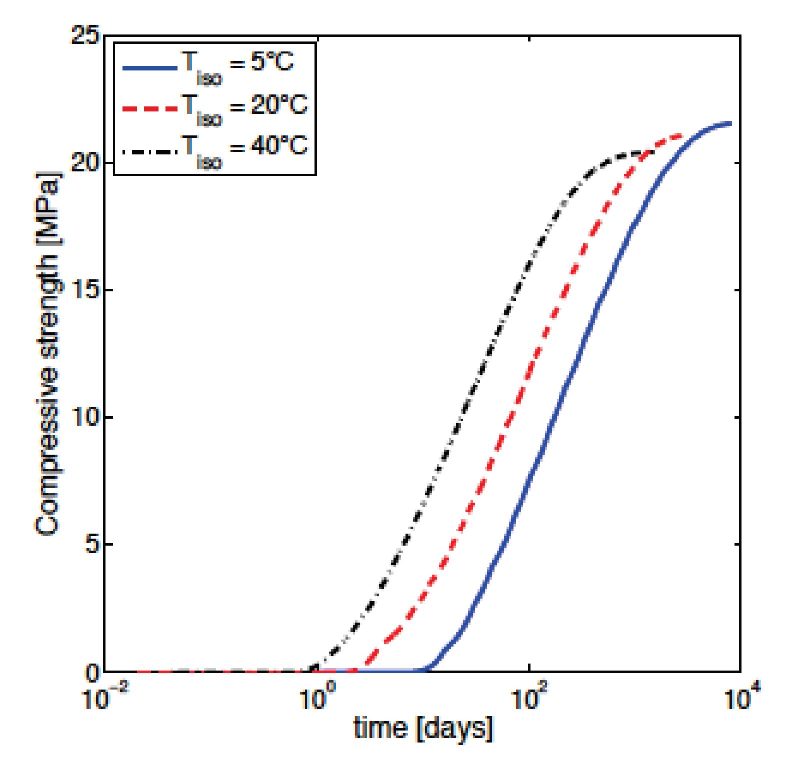
$$\lambda_T(T) = \left(\frac{T_T - T}{T_T - T_{ref}} \right)^{n_T}$$

$$\lambda_{f_c}(\xi) = A_f \cdot \xi + B_f \text{ , for } \xi \geq \xi_{set}$$

$$f_c(\kappa) = \kappa \cdot f_{c,\infty}$$

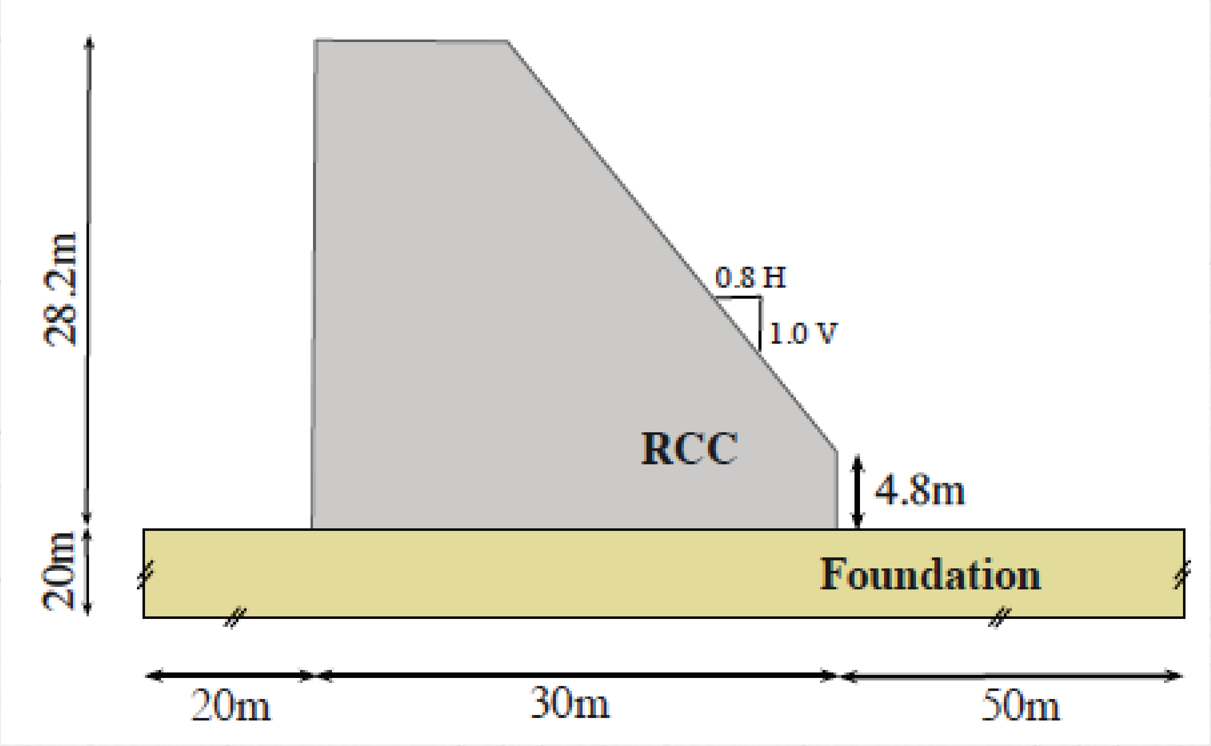
$$E(\kappa) = \kappa^{1/2} \cdot E_\infty$$

$$f_t(\kappa) = \kappa^{2/3} \cdot f_{t,\infty}$$



DAM MODEL

- Results at the end of dam's construction :
  - 2D modeling - plane strain;
  - geometry inspired from Pedrógão dam (Leitão et al., 2007).

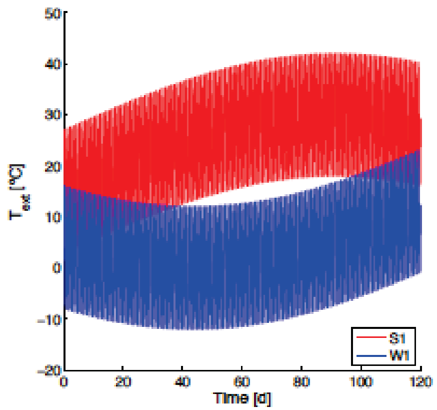


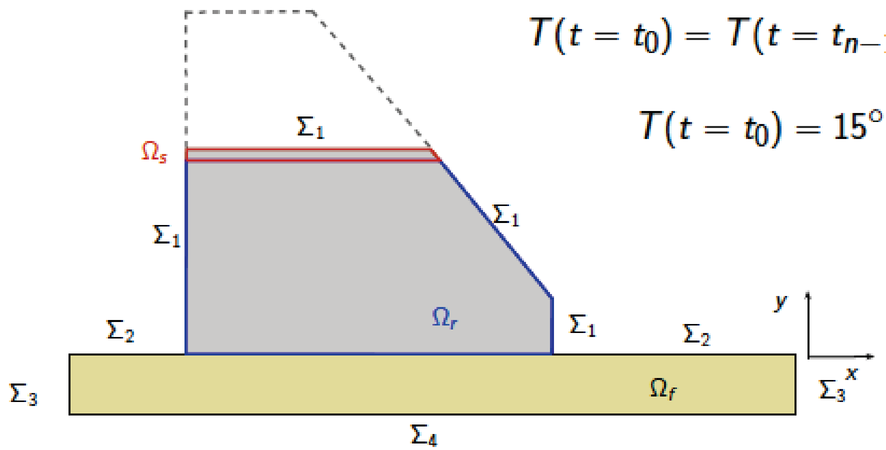
THERMAL BOUNDARY CONDITIONS

$$T(t = t_0) = T_{ext}(t = t_0) + \Delta T_0 \quad \forall(\underline{x}, \underline{y}) \in \Omega_s$$

$$T(t = t_0) = T(t = t_{n-1}) \quad \forall(\underline{x}, \underline{y}) \in \Omega_r$$

$$T(t = t_0) = 15^\circ C \quad \forall(\underline{x}, \underline{y}) \in \Omega_f$$





n = layer number

t_0 = casting instant

$$T_{ext}(t) = T_m + \Delta T_y \cdot \sin(2\pi \cdot f_y \cdot t + \phi_y) + \Delta T_d \cdot \sin(2\pi \cdot f_d \cdot t + \phi_d)$$

$$\frac{\partial T}{\partial \underline{n}} = \begin{cases} \frac{h}{k} \cdot (T_{ext} - T), & \forall(\underline{x}, \underline{y}) \in (\Sigma_1 \cup \Sigma_2) \\ 0, & \forall(\underline{x}, \underline{y}) \in (\Sigma_3 \cup \Sigma_4) \end{cases}$$

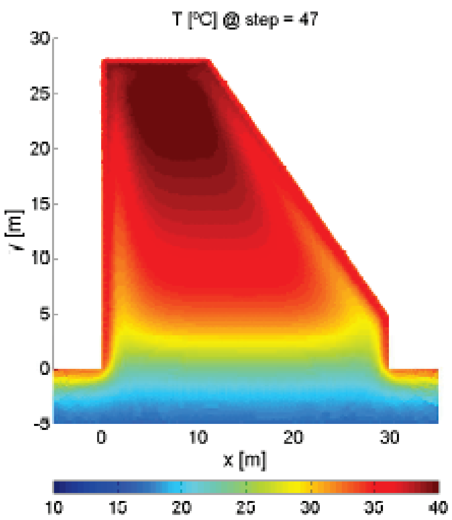
$$h = \begin{cases} h_{rcc} = 27\, W/(m^2\, {}^\circ C) \\ h_{fnd} = 25\, W/(m^2\, {}^\circ C) \end{cases}$$

$$T = 15^\circ C \quad \forall(\underline{x}, \underline{y}) \in \Sigma_4$$

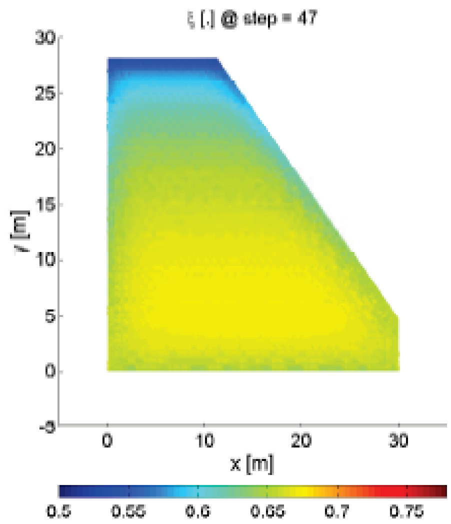
$$k = \begin{cases} k_{rcc} = 2.3\, W/(m^\circ C) \\ k_{fnd} = 2.9\, W/(m^\circ C) \end{cases}$$

DETERMINISTIC RESULTS

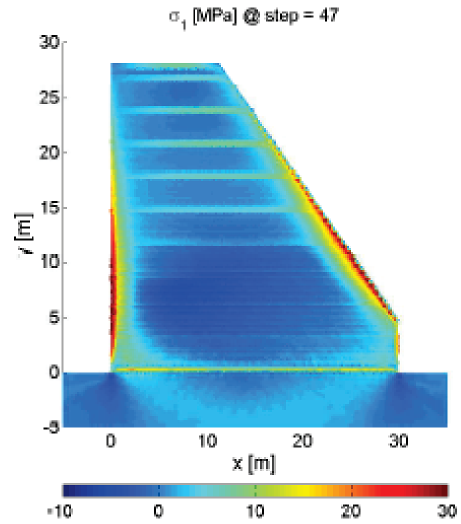
- Results at the end of dam's construction :



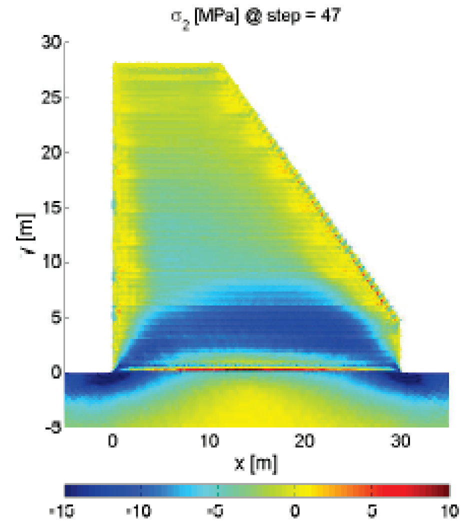
Temperature



Hydration degree

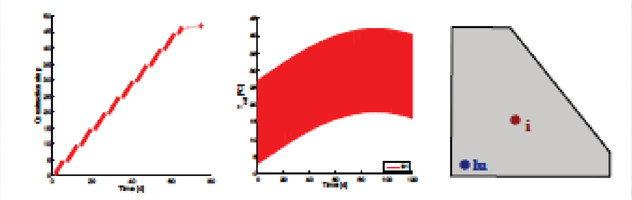


First principal stress

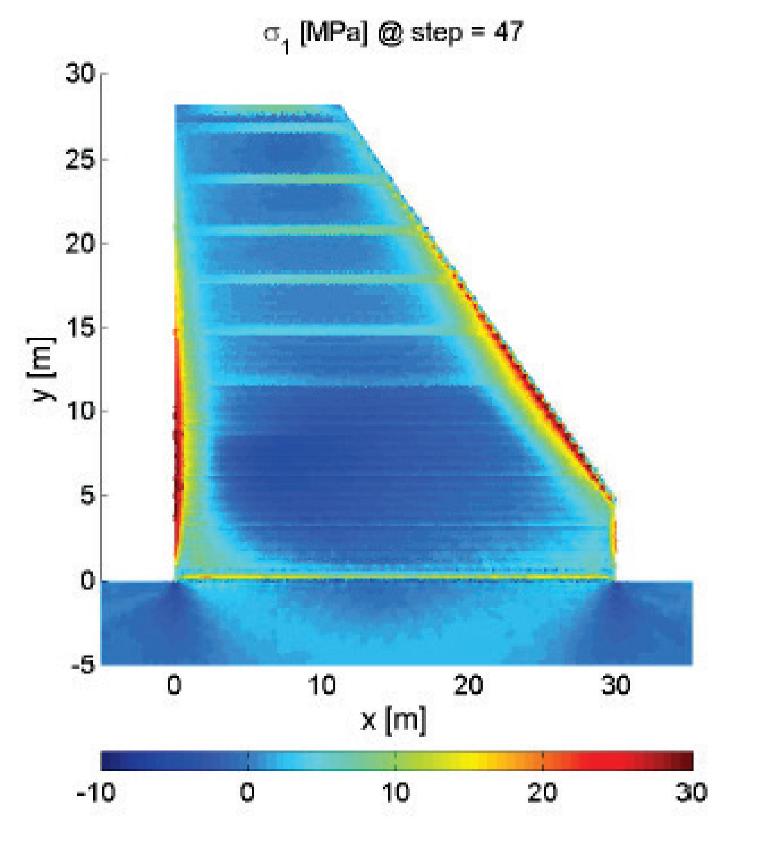


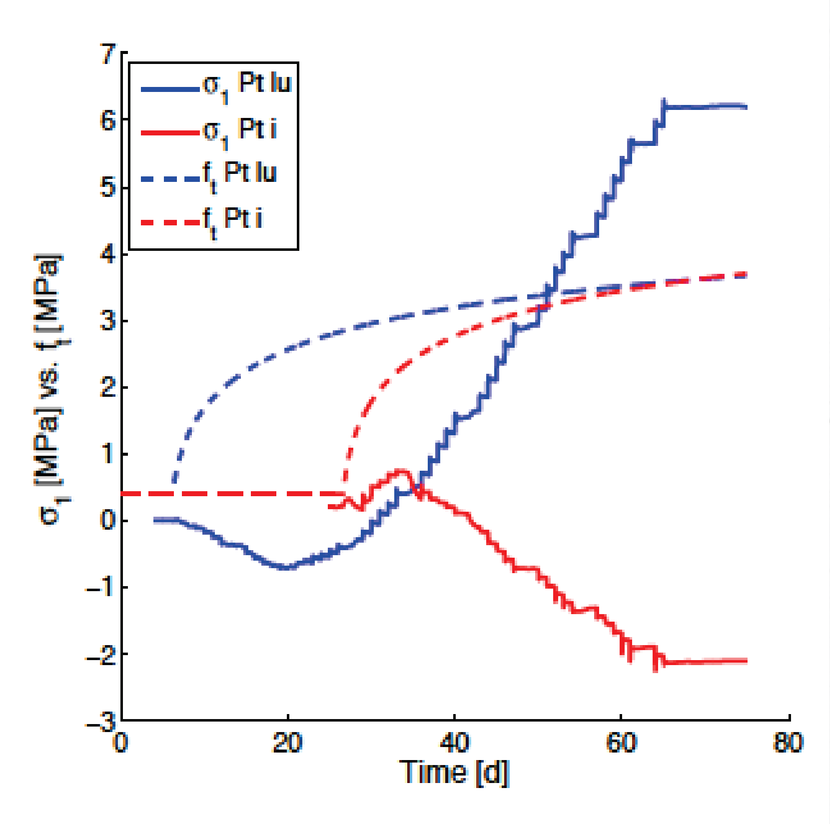
Second principal stress

DETERMINISTIC RESULTS

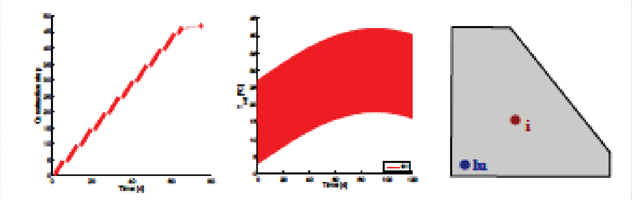


- Results at the end of dam's construction :
  - Tensile strength vs Tensile stress

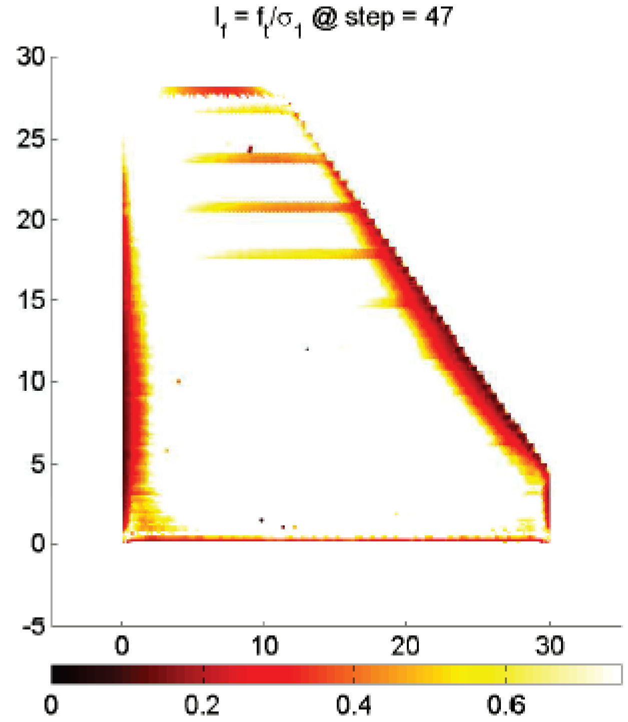




DETERMINISTIC RESULTS

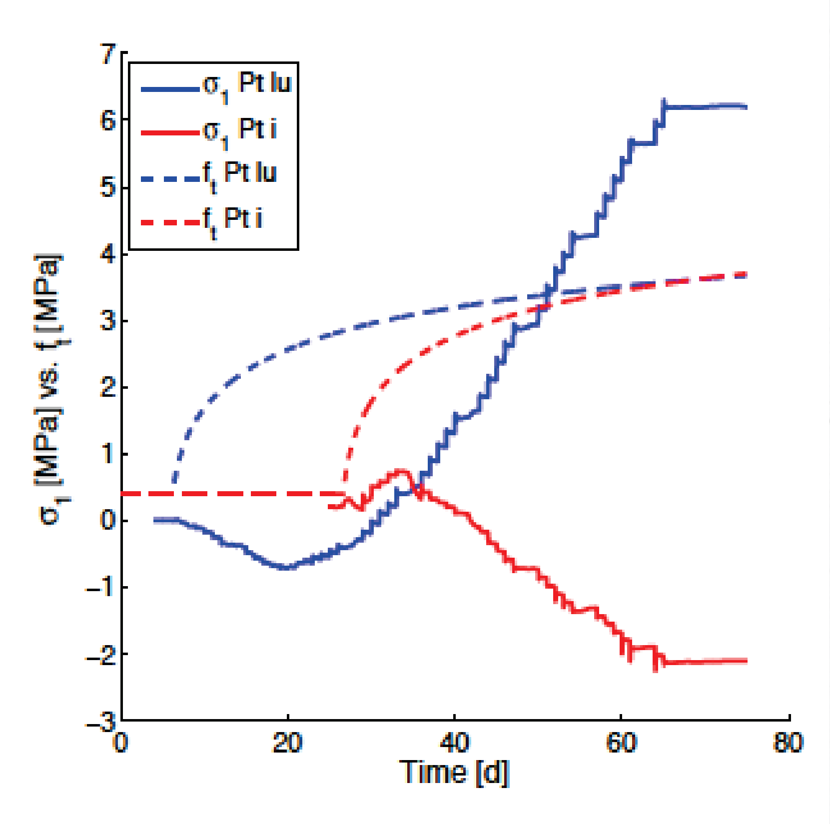


- Results at the end of dam's construction :
  - Tensile strength vs Tensile stress



$I_f = 0$
Completely damaged

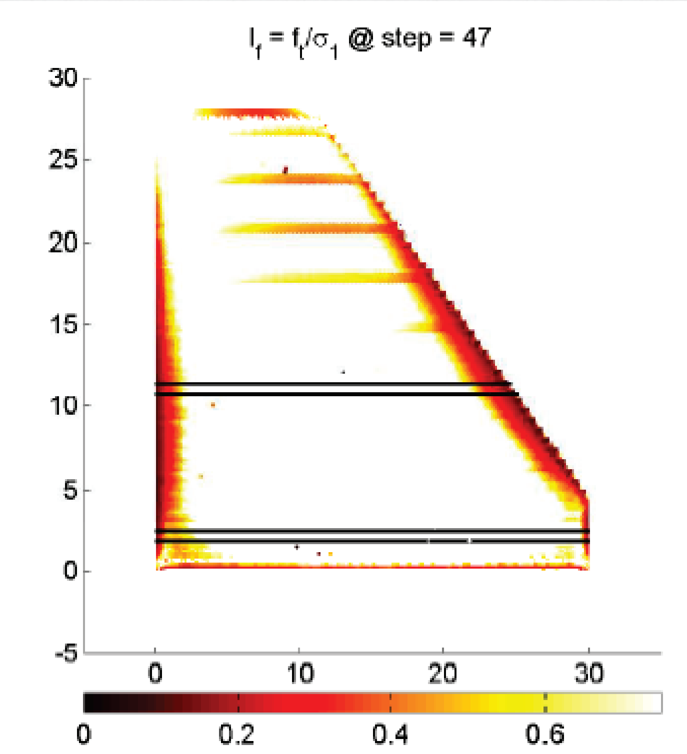
$I_f = I_{f,lim}$
Macrocracking

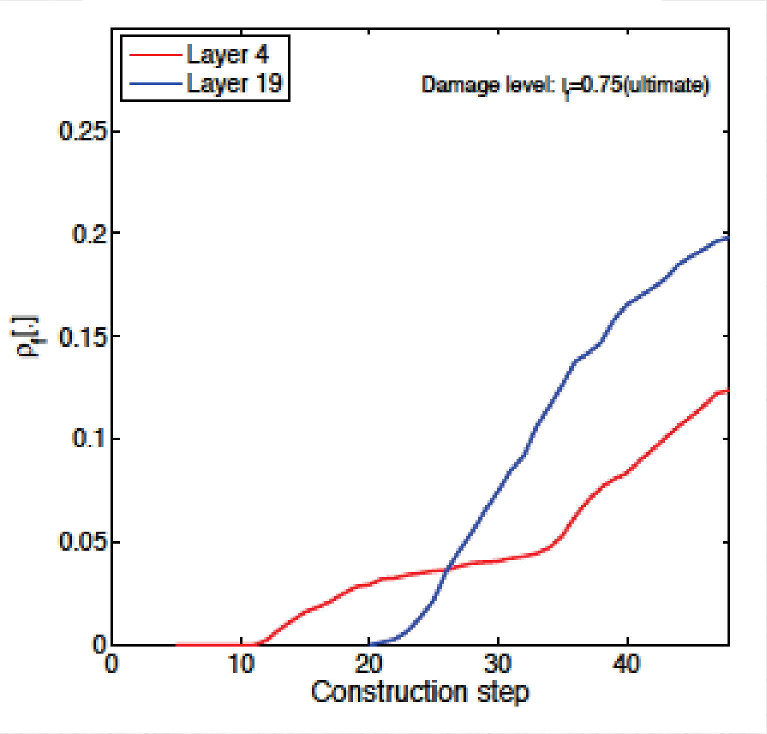


DETERMINISTIC RESULTS

- Measure of "failure" extent :
  - The cracking extent is evaluated at each casted layer by a cracking density concept.

$$\rho_f = N_{0 \leq I_f \leq I_{f,lim}} / N_T$$





UNCERTAINTIES QUANTIFICATION AND PROPAGATION

- Uncertainties
  - into **Vulnerability**: taken into account by giving a random character to the intrinsic material parameters, such as: water-to-cement ratio (w/c), cement content (c), etc. ;
  - into **Hazard**: taken into account by giving a random character to the loads (e.g. wind speed ➔ h[W/(m2·◦C)])
- Objective
  - The aim is to understand how those uncertainties propagate through the model and how their variability will affect the output's variability.
- Sampling methods and Sensitivity Analysis
  - Monte-Carlo based techniques;
  - Global Sensitivity Analysis (Sobol index via RBD-FAST);
  - 2D random fields (for model parameters).

PROBABILISTIC APPROACH

- Uncertainties quantification:
  - six independent random variables;
  - ξ_∞ depends on w/c;
  - I_ξ[kJ/m^3] depends on the cement content c;
  - $f_{t,\infty}$[MPa] and E_∞[GPa] depend on $f_{c,\infty}$.

	w/c[.]	c[kg/m^3]	k[W/(m·°C)]	ξ_{set}[.]	$f_{c,\infty}$[MPa]	ΔT_0[°C]
μ	0.6	220	2.3	0.3	40	2
CV	0.1	0.15	0.25	0.2	0.25	0.5

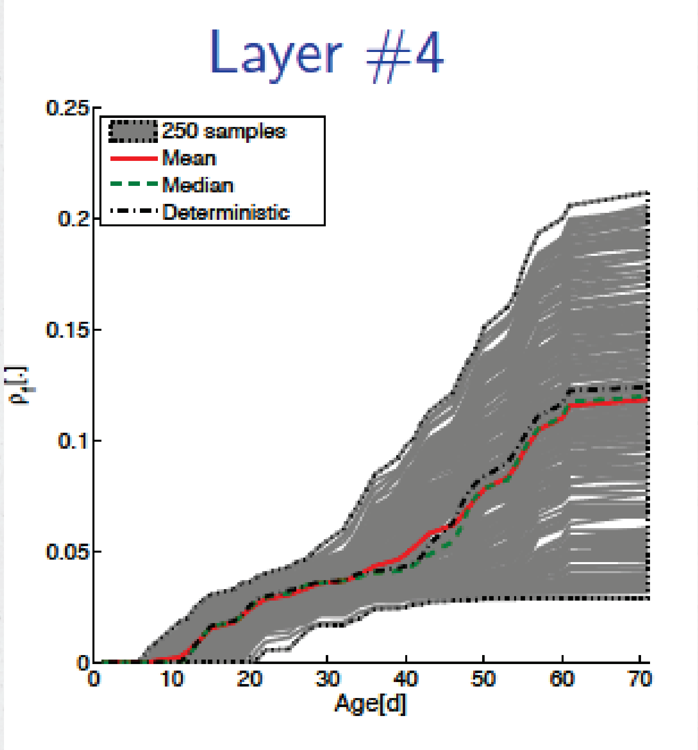
$$\xi_\infty = \frac{1.031 \cdot w/c}{0.194 + w/c}$$

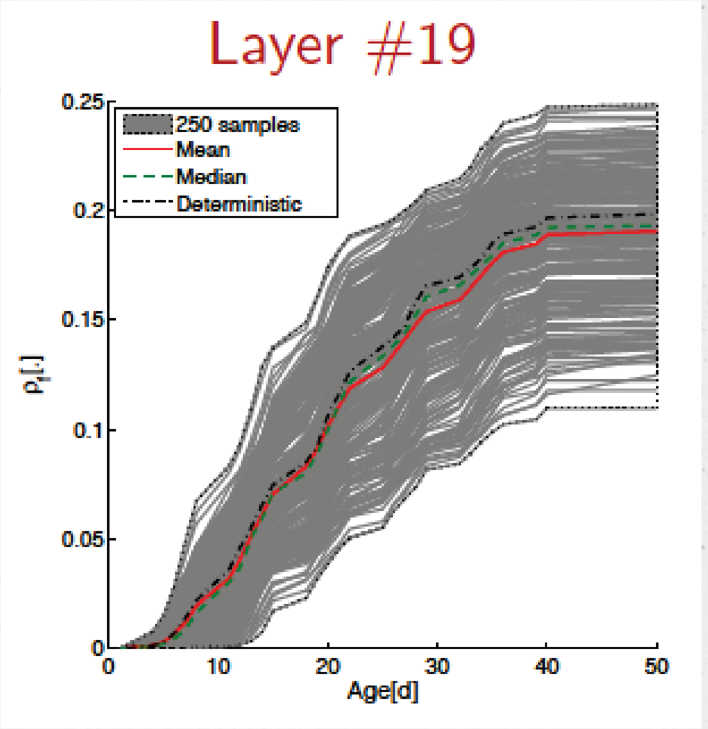
$$I_\xi = c \cdot 284\text{kJ/kg}$$

$$f_{t,\infty} = 0.342 \cdot f_{c,\infty}^{2/3}; \quad E_\infty = 3.95 \cdot f_{c,\infty}^{1/2}$$

PROBABILISTIC APPROACH

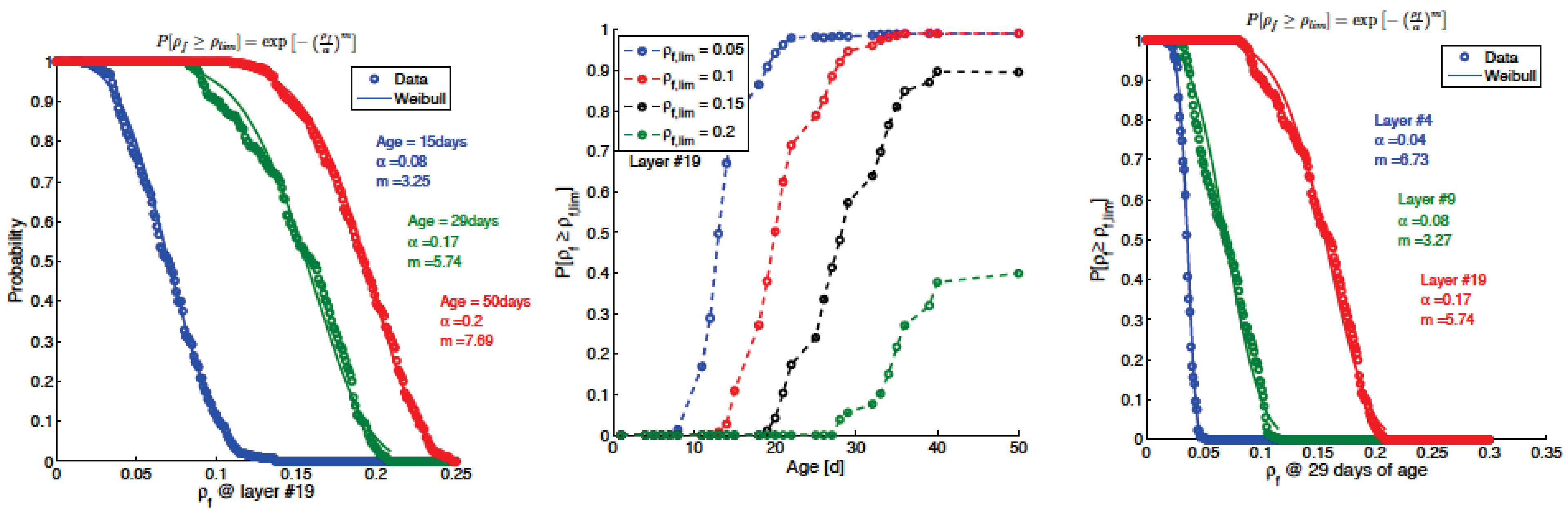
- Uncertainties propagation.
  - 250 computations;
  - cracking density curves on layers #4 and #19.





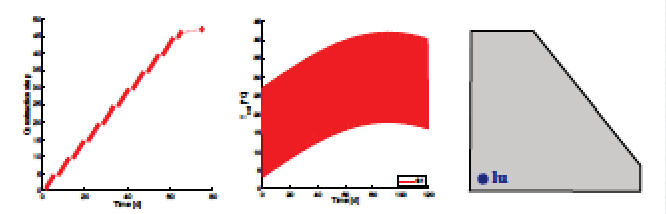
PROBABILISTIC APPROACH

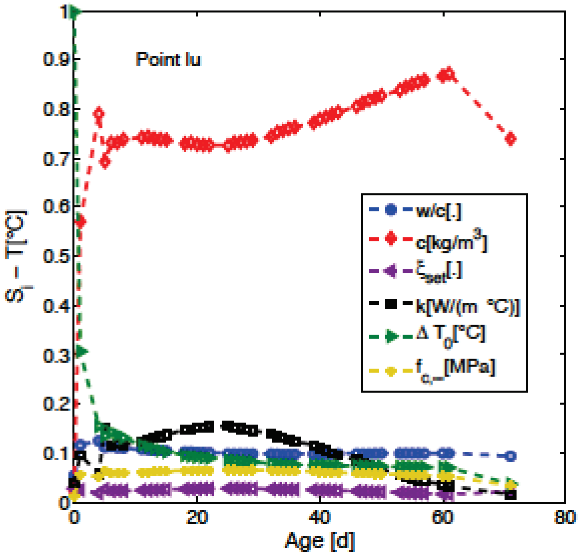
- Cracking density on layer #19
- Statistical analysis over the results and estimation of the probability of exceeding a given cracking density limit $\rho_{f,lim}$



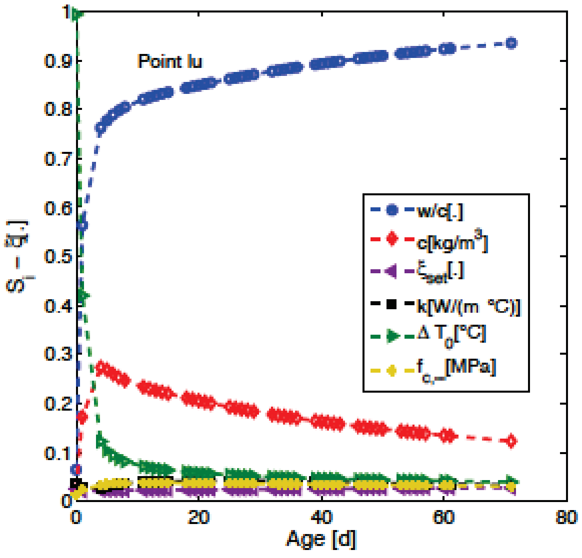
GLOBAL SENSITIVITY ANALYSIS

- First-order sensitivity index

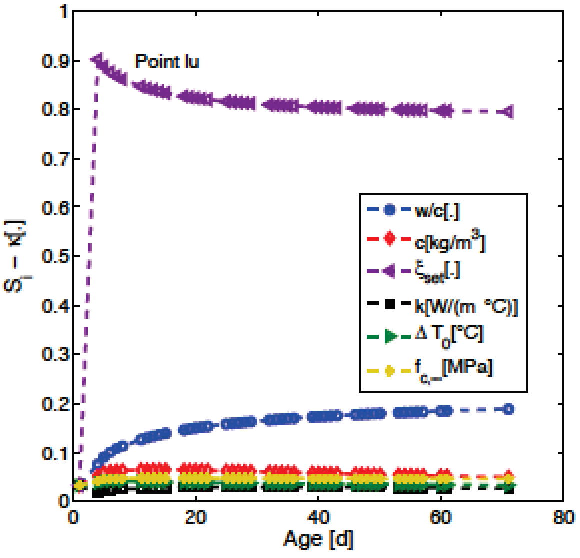




S_i over temperature



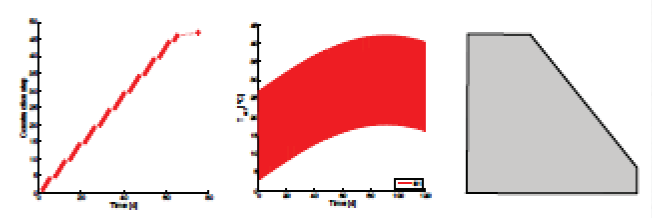
S_i over hydration degree

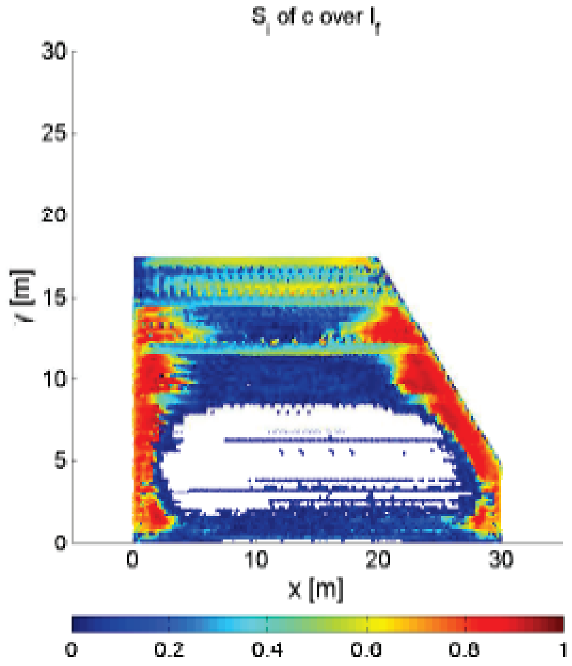


S_i over ageing degree

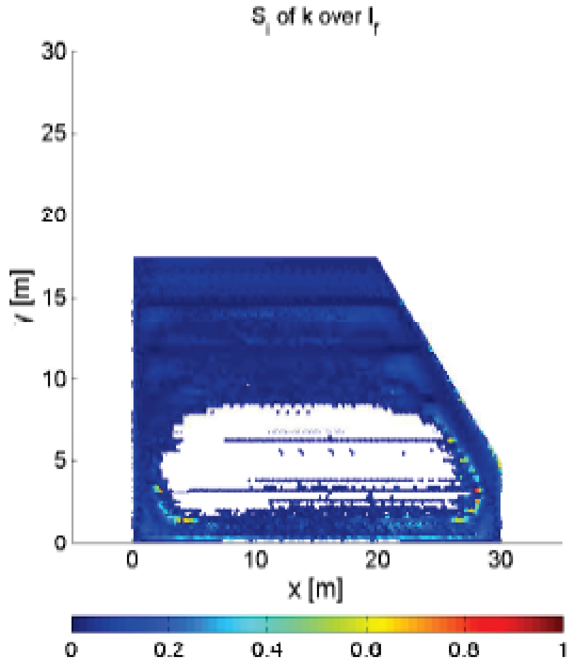
GLOBAL SENSITIVITY ANALYSIS

- First-order sensitivity index





S_i for cement content over I_f



S_i for the thermal conductivity over I_f

MAIN CONCLUSIONS

- probability curves for cracking density within each casted layer as functions of both age and boundary conditions are predicted;
- Weibull distribution fits well the majority of the CCDF curves;
- a unique probability curve is not representative of the entire dam;
- the cement content is the considered random variable which is most affecting the thermal behaviour of the dam and leading to extreme cracking patterns.

TU 1404
COST ACTION

Back to the list of presentations

Objectives and plan of the group priority GP2e – Benchmarking calculations

Laurie Buffo-Lacarrière – University of Toulouse, France

Agnieszka Knoppik-Wróbel – Silesian University of Technology, Poland

Benchmarking calculations in Cost action

Several stages of calculations

⇒ Stage I : simple examples (THC calculations)

⇒ Stage II : extended examples (Mechanical calculations on lab specimens)

⇒ Stage III : case studies (Structural scale)

Several questions raised to organise the work

⇒ Deadline for different stages ?

⇒ Blind or not blind calculations ?

⇒ How many cases mandatory in each stage ?

- **Stage I : Simple examples**
- **Stage II : Extended examples**
- **Stage III : Case studies**
- **Conclusions**

Stage I : THC calculations

See previous presentation of Mateusz in Ljubljana

Validation tests for microstructural and multiscale models

Validation for different W/C ratios

Chen et al. 2013

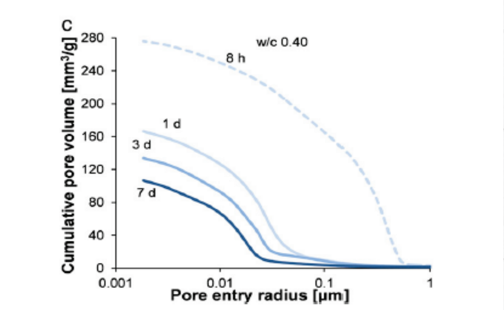


Fig. 6. Size distribution of pore entries measured with MIP for different hydration times for a) w/c 0.30, b) w/c 0.35, and c) w/c 0.40.

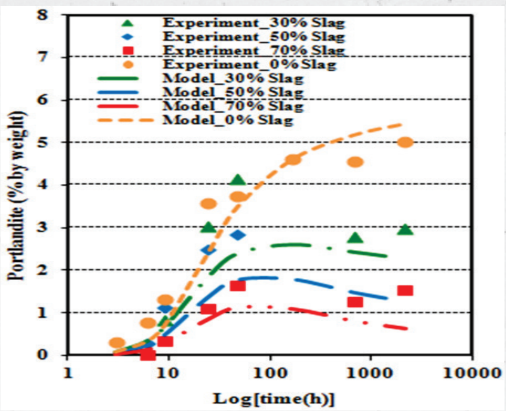
⇒ Input data : Composition, Blaine fineness

⇒ Results : Hydration heat evolution, chemical shrinkage, pore size distribution at several ages

Validation for slag blended cement

⇒ Input data : Composition of cement and slag, Blaine fineness, formula of paste (different cement replacement ratios)

⇒ Results : Hydration heat evolution, bound water and portlandite content at different ages and for different curing temperatures



Kolani et al. 2012

Stage I : THC calculations

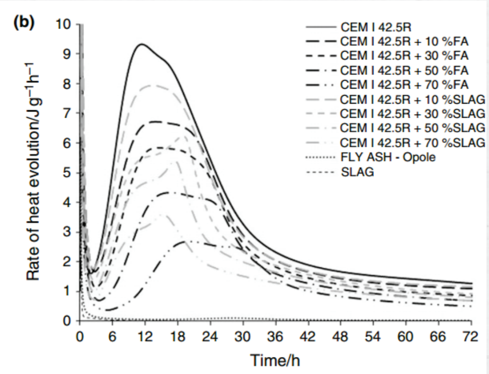
Validation tests for macroscopic and probabilistic models

Heat evolution for blended cement

⇒ Input data : Composition of different blended cements (C+FA and C+Slag), curing temperatures

⇒ Results : Heat development

Klemczak and Batog 2015



Temperature evolution

⇒ Input data : geometry, cement composition, calorimetry at different T [°C]

⇒ Results : Temperature evolution in the centre and on surfaces

Azenha et al. 2011

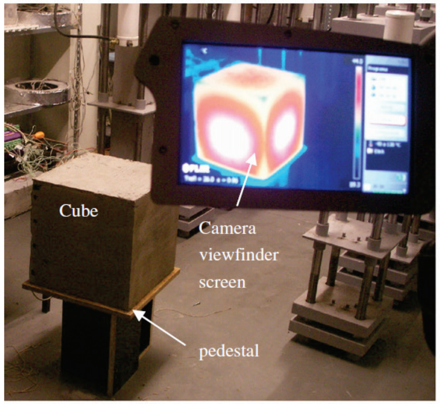


Fig. 2. View of the camera image and spatial relationship with the specimen.

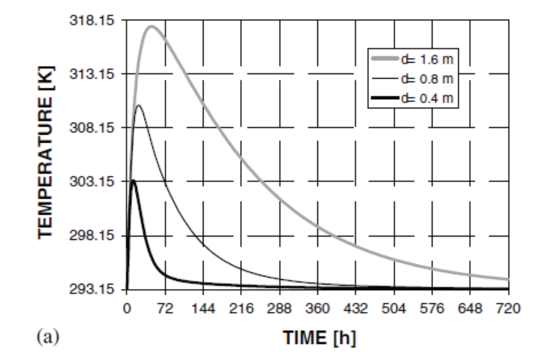
Stage I : THC calculations

Validation tests for macroscopic and probabilistic models

Heat and moisture transport (*numerical test*)

⇒ Input data : Geometry, material properties (calorimetry, sorption, porosity, …)

⇒ Results : Temperature and RH in the centre of the wall *(+ stresses ?)*



Gawin et al. 2006

Effect of boundary conditions (*numerical test*)

⇒ Input data : geometry, cement composition, calorimetry

⇒ Results : Temperature evolution in different points of the wall

Honorio et al. 2014

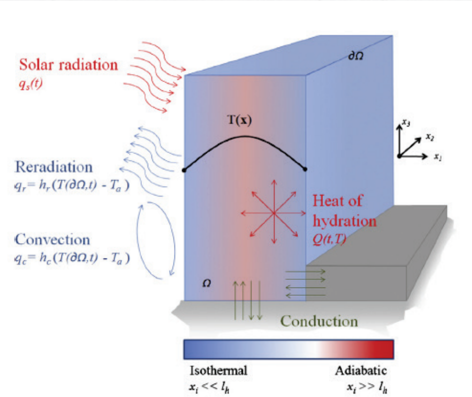


Fig. 1. Schematic representation of the phenomena involved in the chemo-thermal analysis of a concrete structure.

Stage I : THC calculations

Validation tests for macroscopic and probabilistic models

Klemczak and Knoppik-Wróbel 2011

Effect of curing conditions (*numerical test*)

⇒ Input data : geometry, concrete composition, initial temperature, ambient temperature, boundary conditions

⇒ Results : Temperature and moisture content evolution in different points of the slab/wall (+ *stresses ?*)

- **Stage I : Simple examples**
- **Stage II : Extended examples**
- **Stage III : Case studies**
- **Conclusions**

Stage II : Extended examples

RESULTS FROM WG1

Tests for microstructural and multiscale models

Input data and test used for fitting

⇒ Chemical characterisation of Vercors materials — ***GP1 a,b***

⇒ + …

Expected results

⇒ Evolution of microstructure (porosity, hydrates, …) — ***GP1 b,c***

⇒ Evolution of elastic properties

⇒ Evolution of creep properties

⇒ Evolution of fracture properties

} ***GP1 d,e,f***

Stage II : Extended examples

RESULTS FROM WG1

Tests for macroscopic and probabilistic models

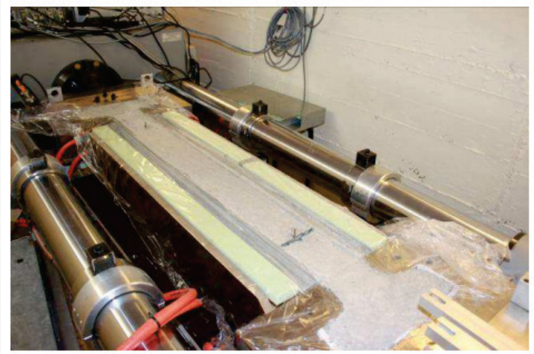
Input data and test used for fitting

⇒ Results from multiscale model

⇒ *Or*: evolution of properties from WG1

Expected results

⇒ Early age THCM behaviour of TSTM specimen



Work of ULB team in WG1

Test on laboratory structure with well controlled experimental conditions

- **Stage I : Simple examples**
- **Stage II : Extended examples**
- **Stage III : Case studies**
- **Conclusions**

Stage III: Case studies

<u>Vercors structure</u>

More information in the following presentation by J. Sanahuja

Why this case study is needed

Vercors concrete is the reference concrete for WG1

⇒ Materials completely characterized

⇒ **Coherence of the global action**

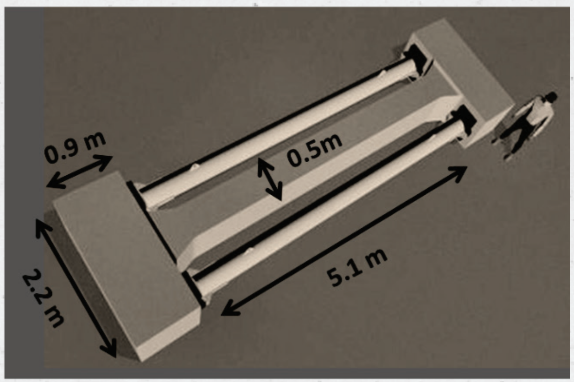
Risks

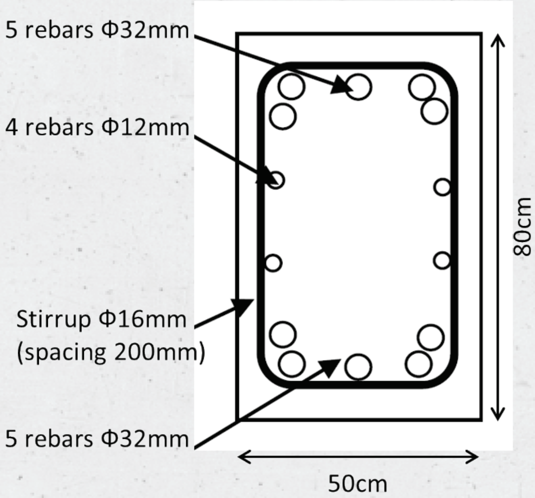
⇒ Boundary conditions were not well controlled

⇒ No too much time for feedback on experimental measurements

Stage III: Case studies

Restrained structures from CEOS project





Why this case study could be interesting

⇒ Structures highly instrumented (temperature, stains in concrete, on reinforcement, crack pattern, …)

⇒ 3 structures with different reinforcement

⇒ Important feedback on measurements

More information in the presentation by J-M Torrenti (tomorrow)

Stage III: Case studies

Other structural case studies

Civaux experimental massive wall

⇒ 2 walls cast on slab

⇒ Different concretes (CEM V and CEM I)

More information in the presentation by J-M Torrenti (tomorrow)

Stage III: Case studies

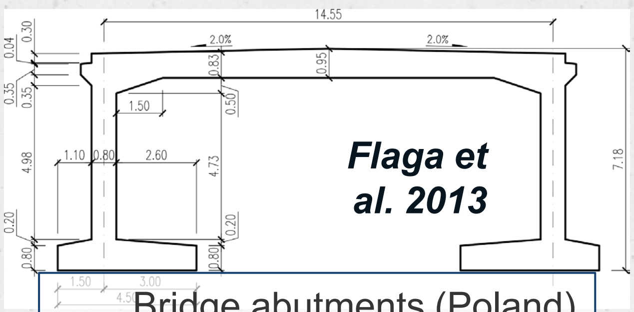
Other structural case studies

Investigation of real structures

⇒ Input data : geometry, concrete composition, initial temp. of concrete, environmental conditions (ambient temp., sometimes RH of air, wind), surface protection

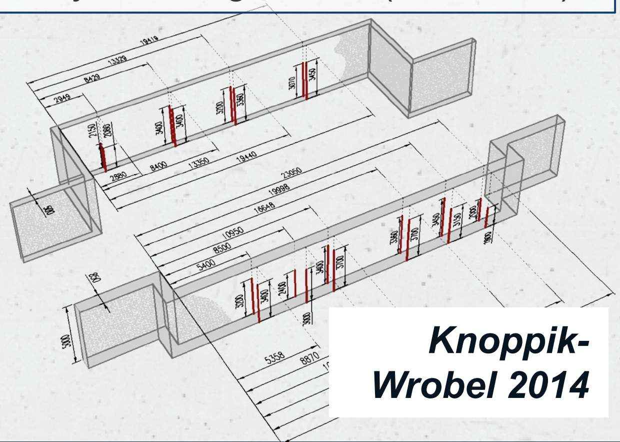
⇒ Results : cracking pattern, width of cracks (sometimes)

⇒ **What is lacking :** temperature evolution measurements, strain measurements

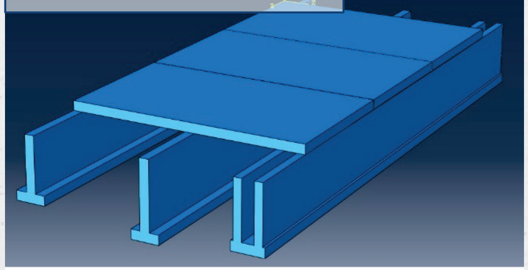

Bridge abutments (Poland)

Flaga et al. 2013

X-ray shielding bunker (Near East)


Knoppik-Wrobel 2014

Tunnel in Sweden


Hösthagen et al. 2014

- **Stage I : Simple examples**
- **Stage II : Extended examples**
- **Stage III : Case studies**
- **Conclusions**

Keys for a successful benchmarking program?

- **Good knowledge of the chosen structure**

Large experimental campaign on the Vercors project

"Overview of the Vercors project" ***by J. Sanahuja***

- **Benchmark organization**

What are the data to give? Can teams choose to adapt some input data? …?

"Experience of the team FEUP/Uminho in Concrack benchmark" ***by M. Azenha***

- **Feedback on the in-situ measurements**

How to analyze the obtained data? Specificities for hardening concrete?

"Lessons learned from in-situ measurements in hardening concrete" ***by D. Schlicke***

Conclusions

	Stage I		Stage II		Stage III
	Micro / Multiscale	**Macro / Proba**	**Micro Multiscale**	**Macro Proba**	
Tests	1. Effect of W/C 2. Effect of cement replacement ratio	1. Heat for blended cement 2. Heat-Moisture 3. Cube temp. 4. Effect of BC	Evolution of mech. properties	TSTM (1 among ≠ tests)	Vercors + CEOS + Civaux ? + Real struct.
Dates	ASAP		Needs WG1 partial results		Needs WG1 complete results
Blind or not?	No (published results)		??		No (published results)
	In each GP2 (a,b,c,d)		??		In GP2e

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Overview of the VeRCoRs Project

Benoit MASSON, Manuel CORBIN – EDF SEPTEN, France
Sylvie MICHEL–PONNELLE, Gautier MOREAU,
Jean-Philippe MATHIEU – EDF R&D, France

EDF

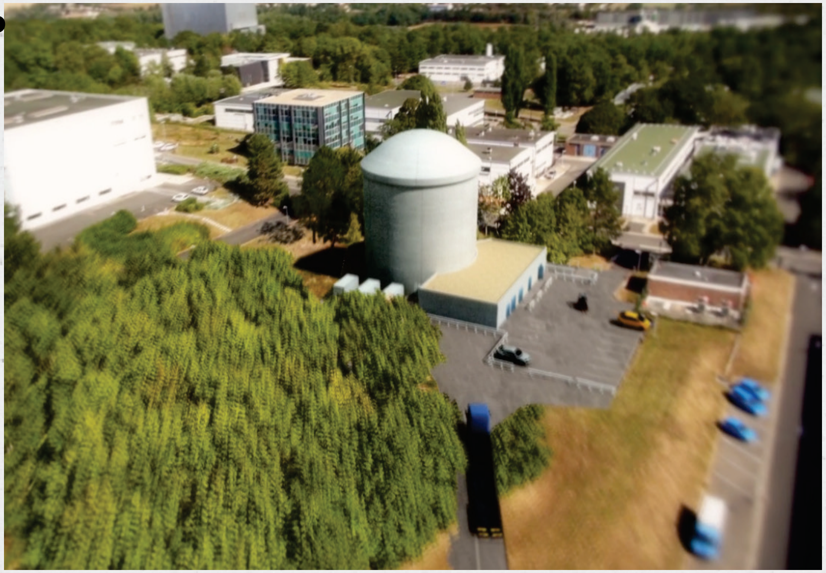
Context of the VeRCoRs Project :

EDF Target

Continuous effort on the safety and life extension of the nuclear power plant

Main objectives of the VeRCoRs Mock up

- Give confidence in the behavior under severe accident conditions
- Study the evolution of the leak tightness under the effects of the ageing
- Study the behavior at early age
- Experiment monitoring and NDE techniques



The VERCOS mock-up supports both industrial and research objectives

Progress of the civil works (1/2): dome

28/04/2015 : End of erection of the inner containment

Progress of the civil works (2/2): pre stressing

Pre stressing of the whole containment performed from may to august 2015

General information about the benchmark

International Benchmark

Theme 1 : Mock-up at early age

Theme 2: Containment history

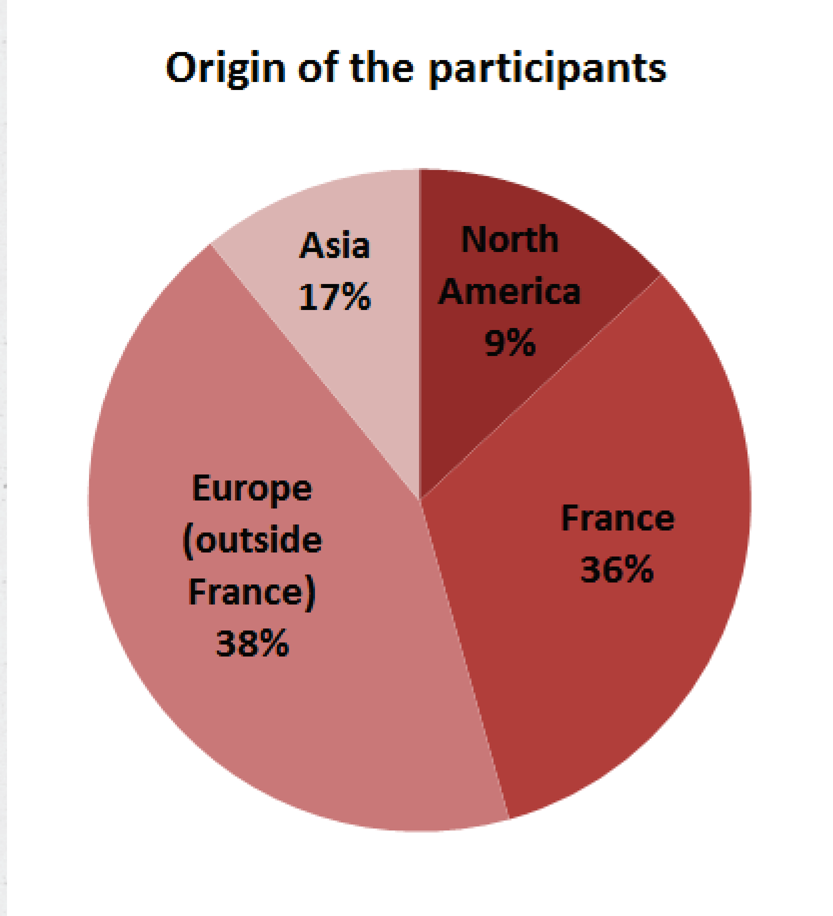
May 2015 : Preliminary results

Total

- ✓ 47 registered participants
- ✓ 18 countries involved across 3 continents
- ✓ 50%: Industrial companies
- ✓ 50%: Universities and research centers

Preliminary submissions per theme

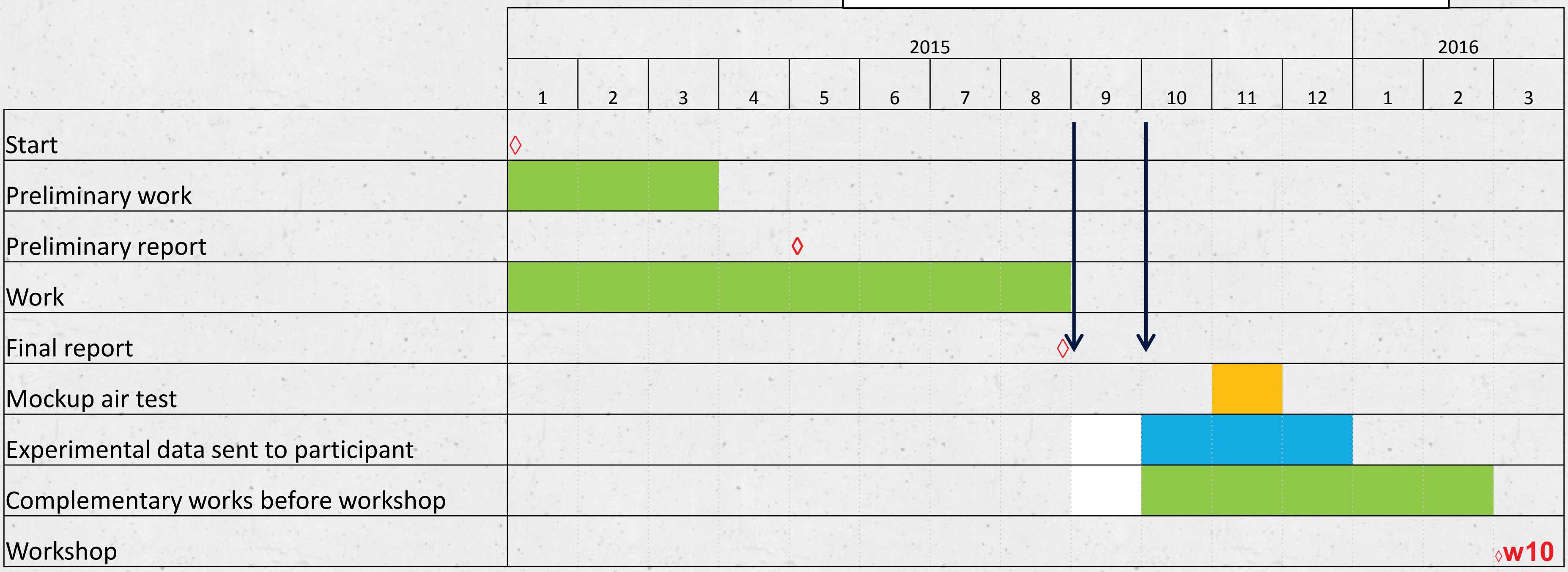
- ✓ Theme 1 : 11 reports
- ✓ Theme 2: 7 reports



For more information : www.fr.amiando.com/EDF-vercors-project

Schedule and key dates

Postponement of the final work submission date to 2nd October



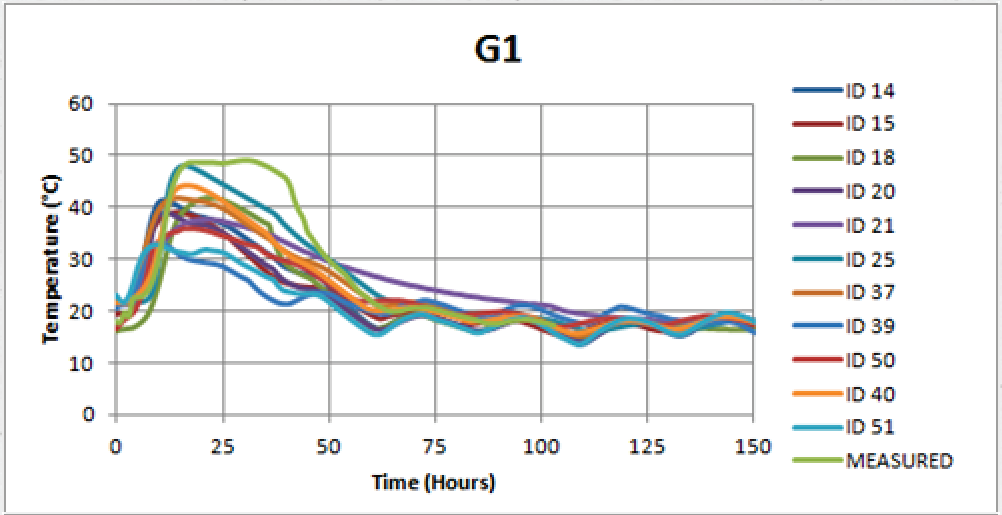
Save the date : the workshop will take place from the 7th to the 9th of March 2016.

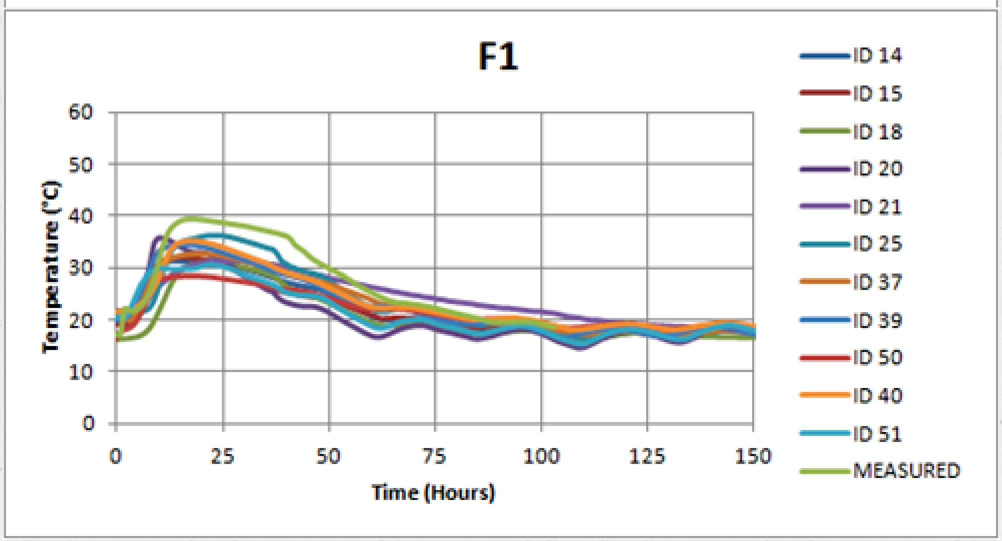
Theme 1 : Early age

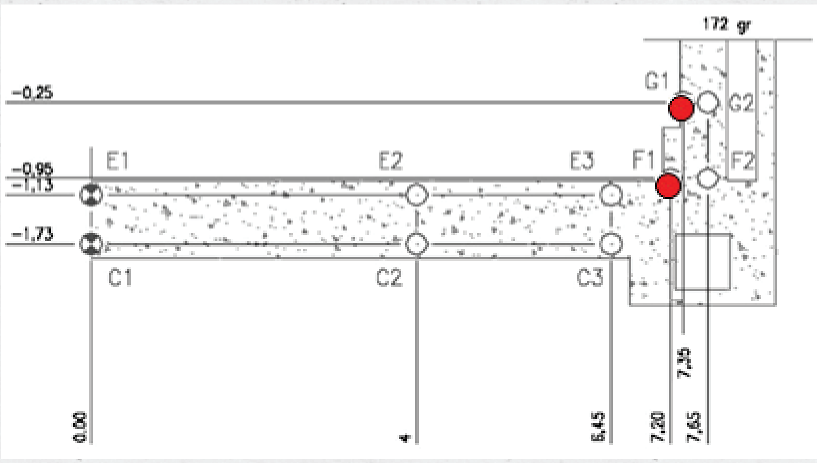
- Reminder of the global work :
  - Prediction of the early age behavior of the gusset, since its pouring up to ten months (end of erection of the whole containment).
- Preliminary work :
  - Forecast of the gusset’s temperature history:

    1 month period after placement.
- Preliminary report (following slides):
  - Comparison of submitted temperature histories
  - Analysis, comments and input data adjustment

Theme 1 : Early age





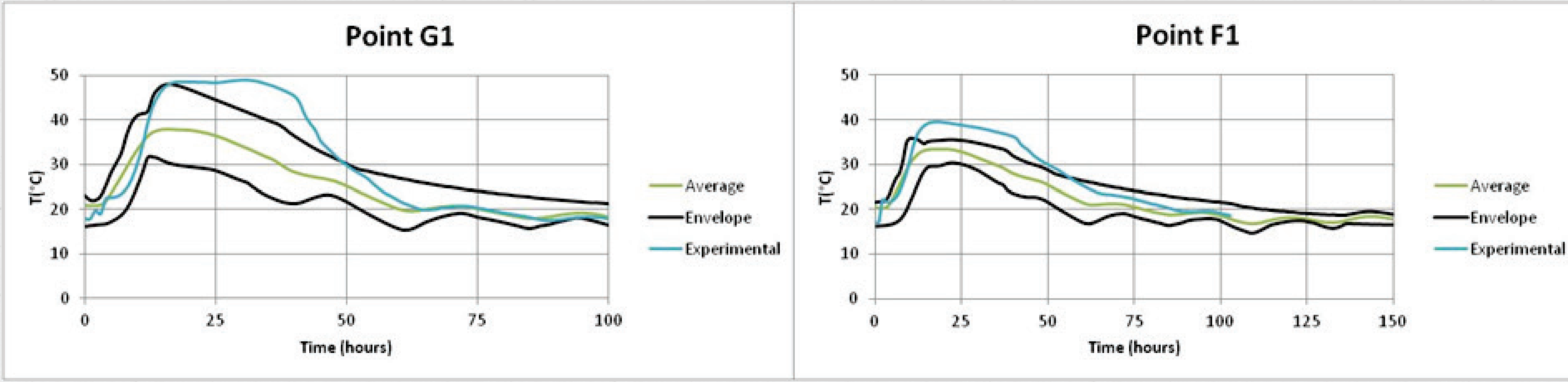


Results analysis:

- Temperature values are underestimated during the first 50 hours
- The experimental temperature plateau (between 10 and 35 h) was not found

Theme 1 : Early age

- *Statistics*



- *Comments*

- Underestimation of temperature values can be due to a poor evaluation of the heated air temperature around the gusset.
- The obtaining of the plateau is directly linked to the duration of the air heating around the gusset.

Theme 1 : Propositions and conclusion

- Findings :

  - The thermometer providing the heated air temperature around the gusset has malfunctioned.

  - There is a difference between the theoretical geometric positions of sensors and the ones reported after execution phase.

- DATA adjustment for the final report:

  -Due to the unreliable measurement of the heated air temperature around the gusset, new boundary conditions must be used.

  Numerical analysis performed at EDF shows better results with the following B.C.

  - ✓ *2 blowers: Increase of air temperature by 20°C*
  - ✓ *4 blowers: Increase of air temperature by 30°C*

  - The heated air temperature curve is updated

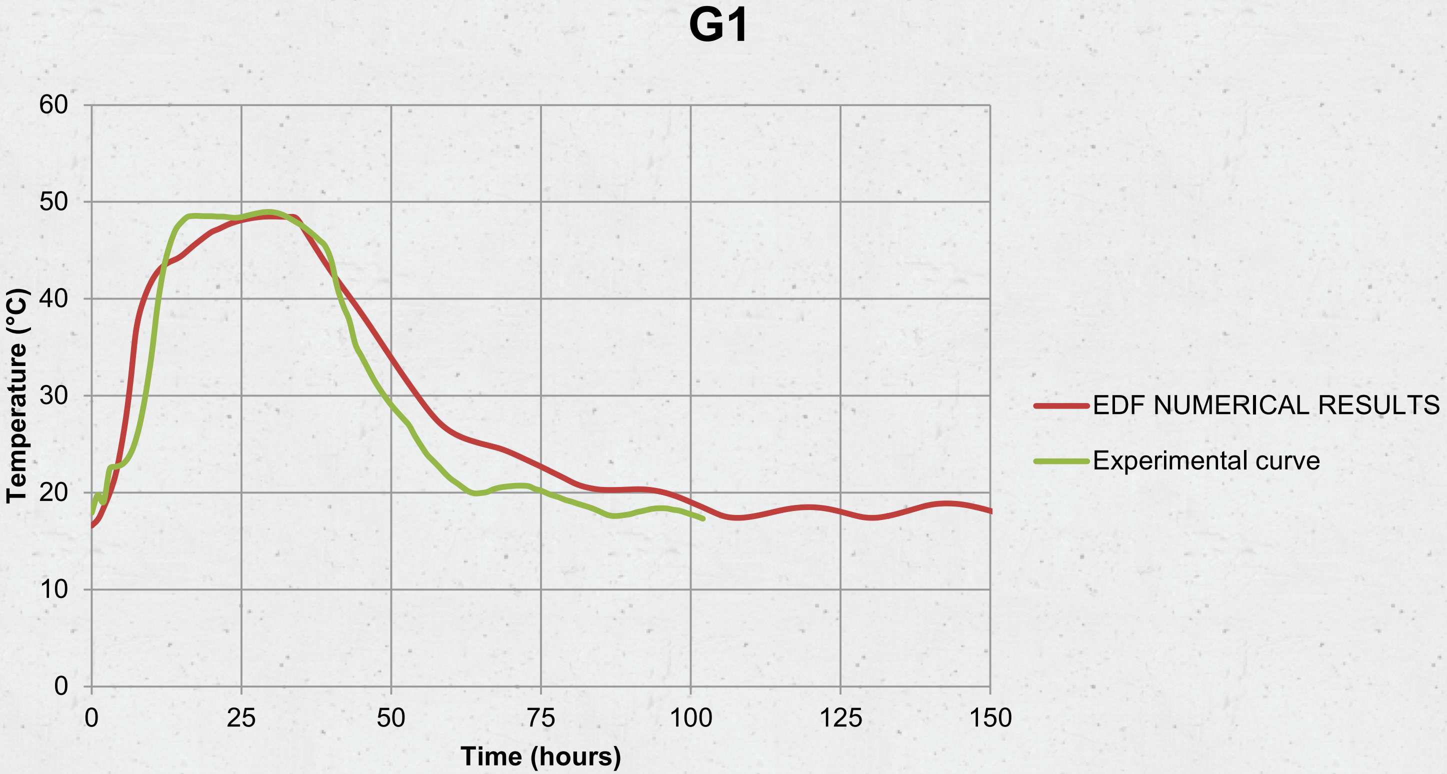
  - 3 PT100 sensors are used at each level (including one in the middle)

  The positions of sensors are updated

Theme 1 :EDF proposition of Gusset BC

- Convective exchange with heated air temperature

    2 blowers: T_heat = T_air + 20°C || 4 blowers: T_heat = T_air + 30°C

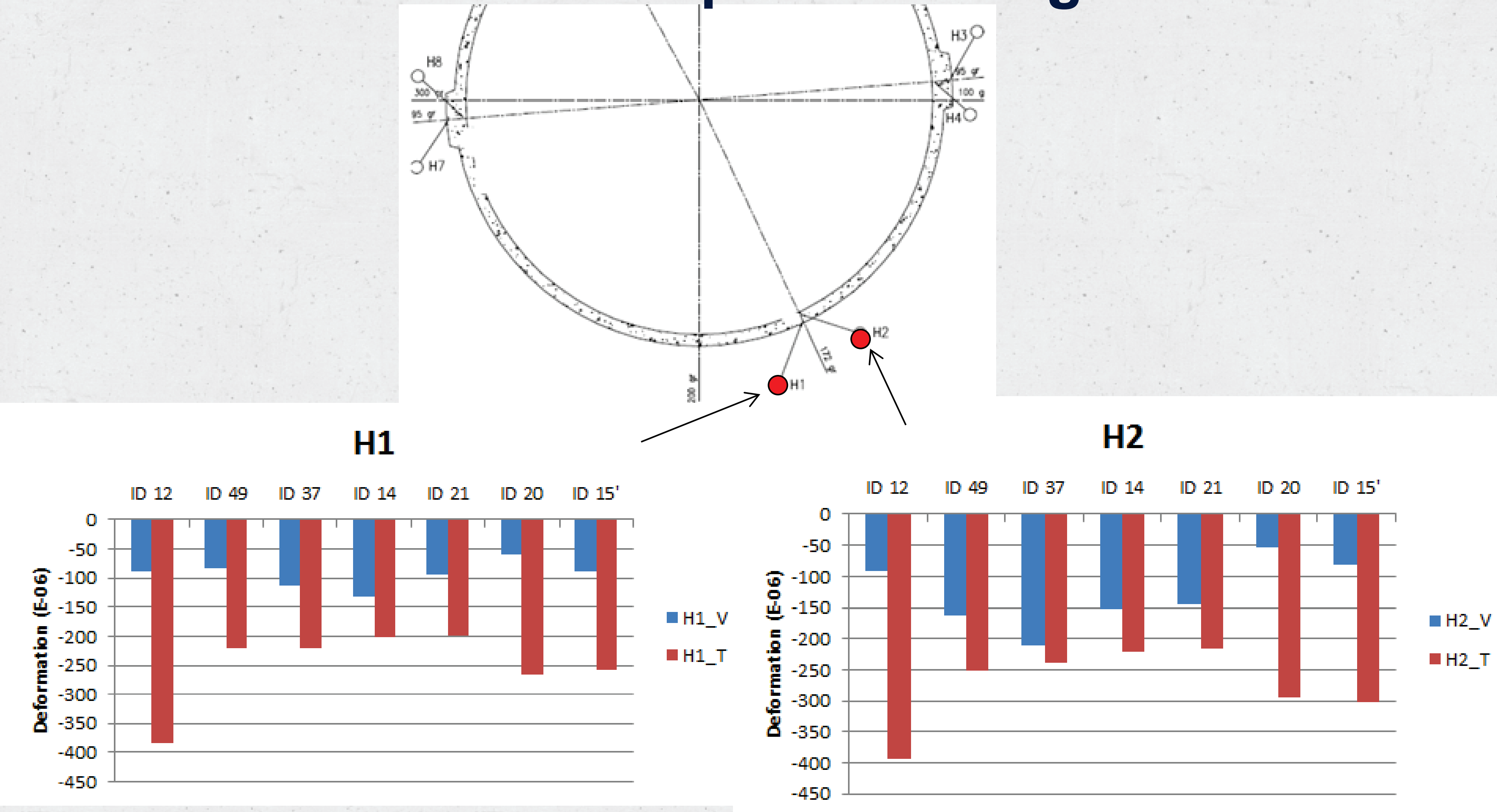


Theme 2 : Containment history

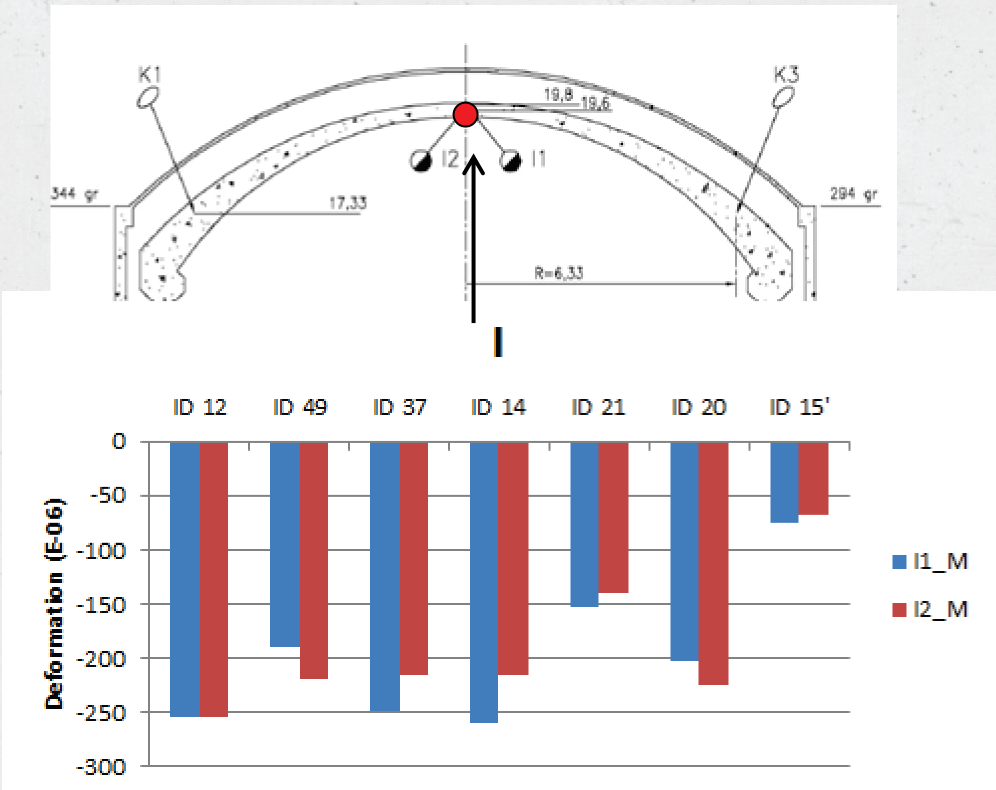
- Reminder of the global work :
  - Prediction of deformations, stresses and cracking history of the whole containment wall (before/after pre stressing, after pressurization test,…)
- Preliminary work :
  - Calculation of deformations due to pre stressing (initial state = just before pre stressing; final state = end of pre stressing) and in sequence, deformations due to pressurization test.
- Preliminary report (following slides):
  - For specific points: comparison of submitted deformations
  - First analysis and comments

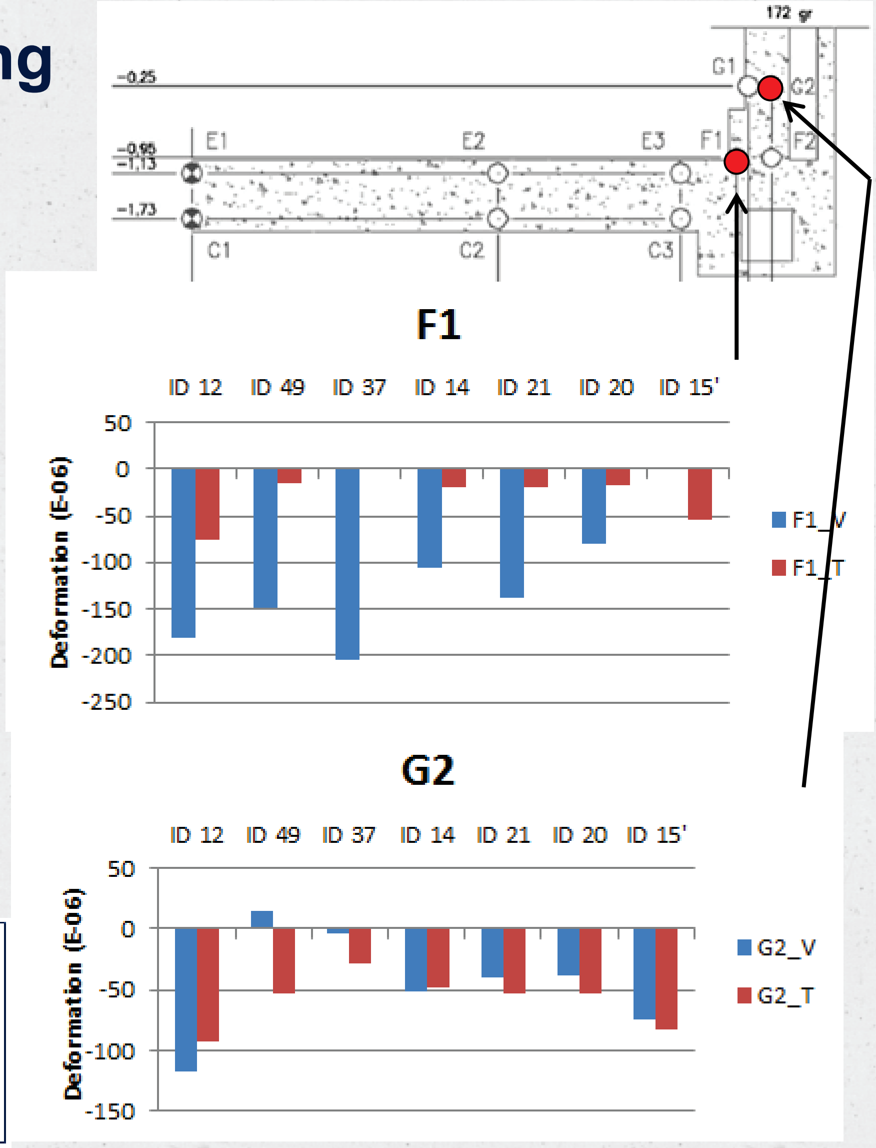
The experimental results are not yet known

Theme 2 : Containment history
Deformations due to pre stressing



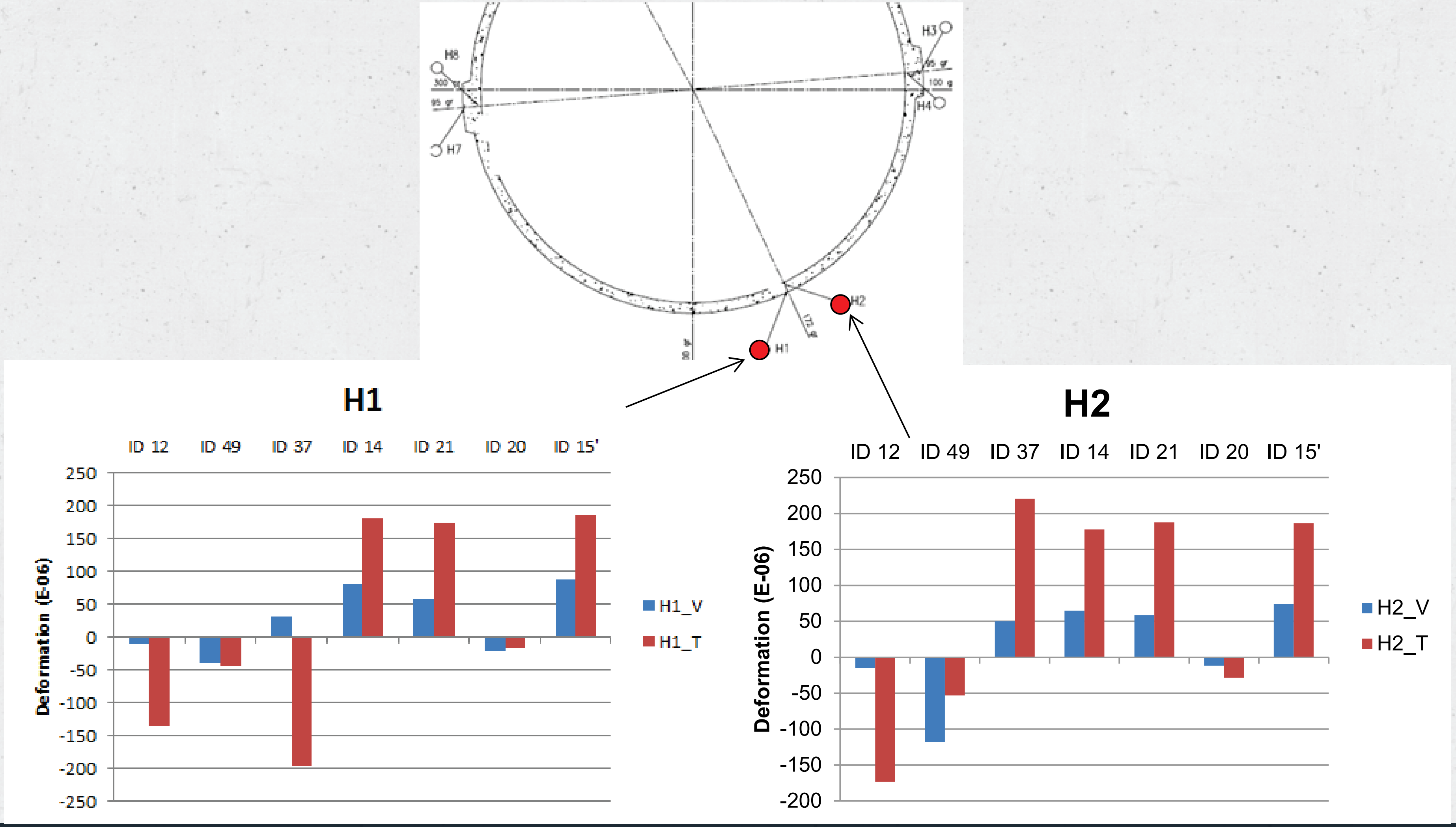
Theme 2 : Containment history
Deformations due to pre stressing



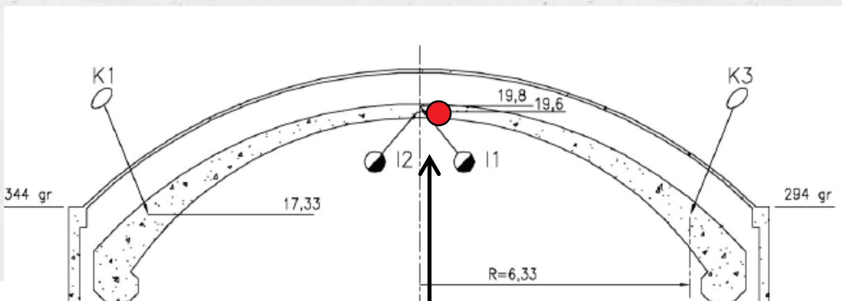


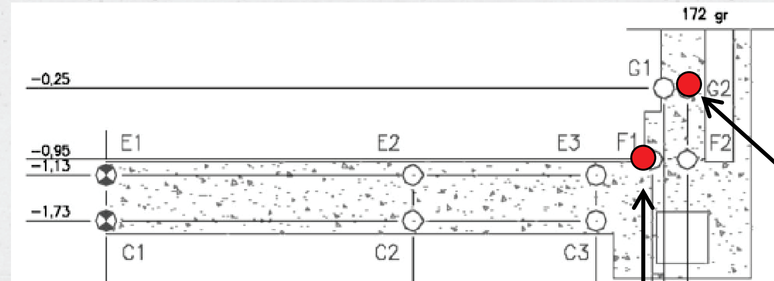
- Overall : Numerical results are consistent
- Differences are due to various initial states definition before pre stressing and to diverse estimations of pre stressing losses due to relaxation and friction of tendons.

Theme 2 : Containment history
Deformations due to pressurization



Theme 2 : Containment history
Deformations due to pressurization





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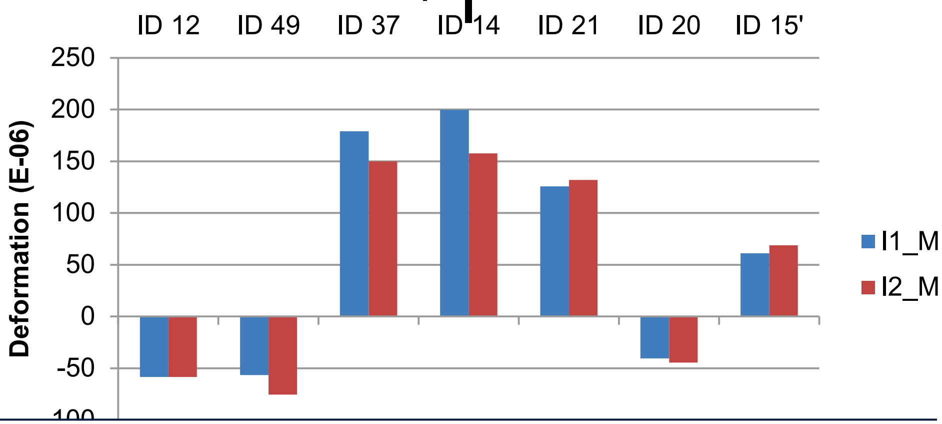

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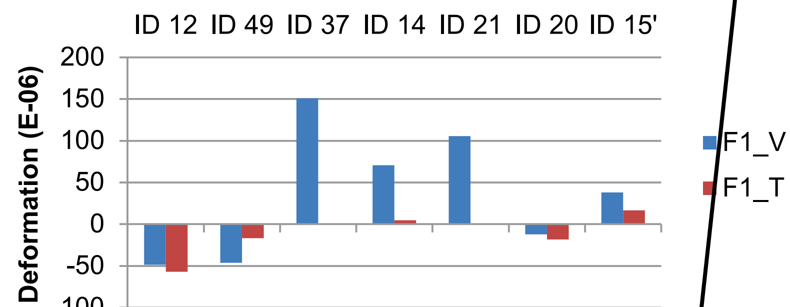

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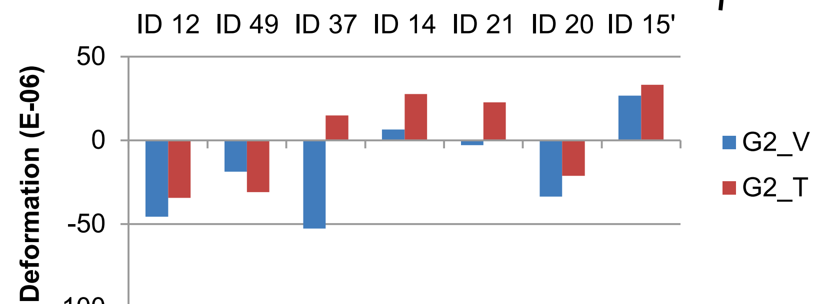


A lot of differences :

- Due to pre stressing, pressurization induces a loss of compression rather than pure tension
- →Some results include only pressurization, others include both pressurization and pre stressing loads.
- Some participants considered a relative pressure of 5.2 bars. The prescribed value is 4.2 bars.

General Conclusions of the Theme 2

– *Results*:

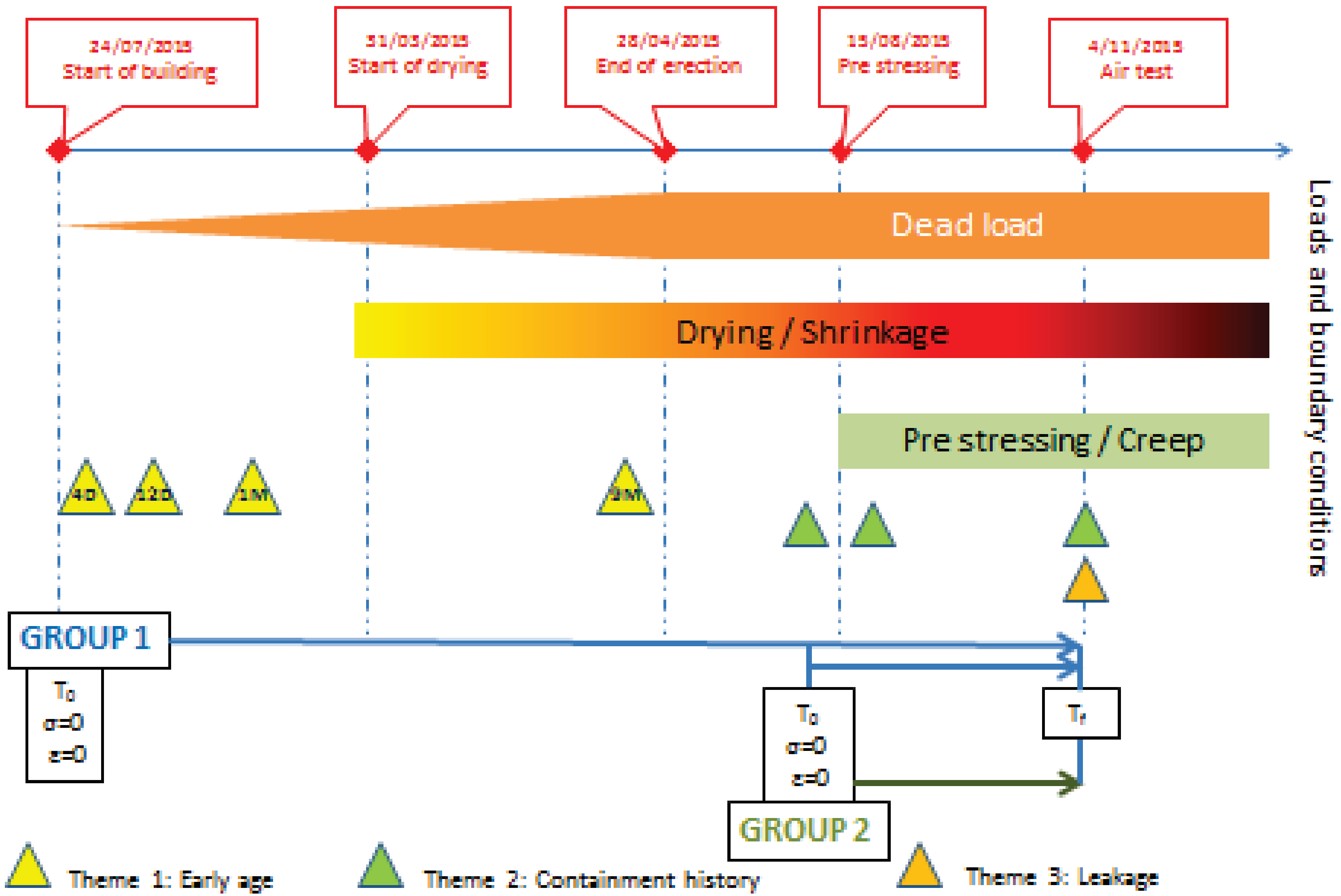
- Despite some differences in the evaluation of tendons pre stressing losses, pre stressing effect is generally consistent.
- Some results given after pressurization do not include pre stressing load
- A misinterpretation of the relative pressure value is observed.

– *Propositions for the final work* (will be detailed on the web site):

- Two groups of results are expected (see scheme next slide):
  - ✓ Group 1 : For those who contribute to theme 1, two results have to be submitted.

    - The first with an initial state corresponding to concrete placement. The following calculations shall take into account the early age behavior of concrete.

    - The second with an initial state just before pre stressing (this, in order to allow a comparison with Group 2)
  - ✓ Group 2 : For those who are not contributing to theme 1, the initial state is just before pre stressing, the structure is assumed fully erected submitted to its own weight.



Start of building
Start of drying
End of erection
Pre stressing
Air test
Dead load
Drying / Shrinkage
Pre stressing / Creep
Loads and boundary conditions
4D
12D
1M
3M
GROUP 1
T_0
$\sigma=0$
$\varepsilon=0$
T_0
$\sigma=0$
$\varepsilon=0$
T_f
GROUP 2
Theme 1: Early age
Theme 2: Containment history
Theme 3: Leakage

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Experience of the team of FEUP/UMinho in the CONCRACK benchmarking program

Miguel Azenha - University of Minho, School of Engineering. Portugal

Rui Faria - University of Porto, Faculty of Engineering, Portugal

Mário Pimentel - University of Porto, Faculty of Engineering, Portugal

Universidade do Minho
Escola de Engenharia

isise Institute for Sustainability and Innovation in Structural Engineering

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

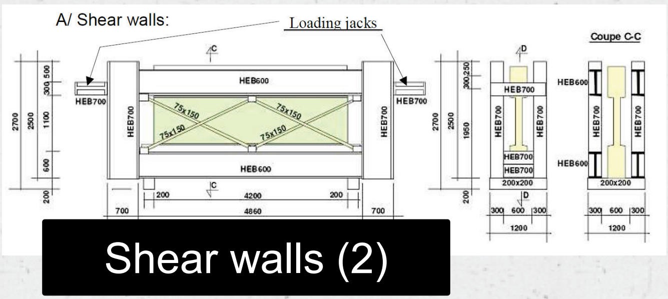
CONSTRUCT

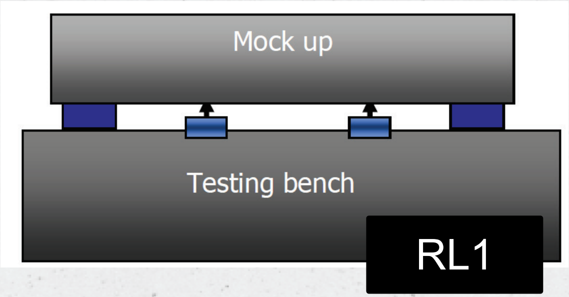
Introduction

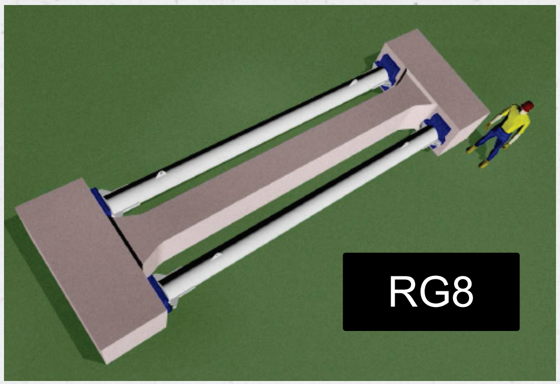
ConCrack.org

CEOS.fr

- International benchmark CONCRACK – CEOS.fr
- Set of 4 challenges for participants: 2 shear walls and 2 large beams (RL1 and RG8)
- Team Porto/Minho – number 10
- Experience in similar situations: consultancy; monitoring





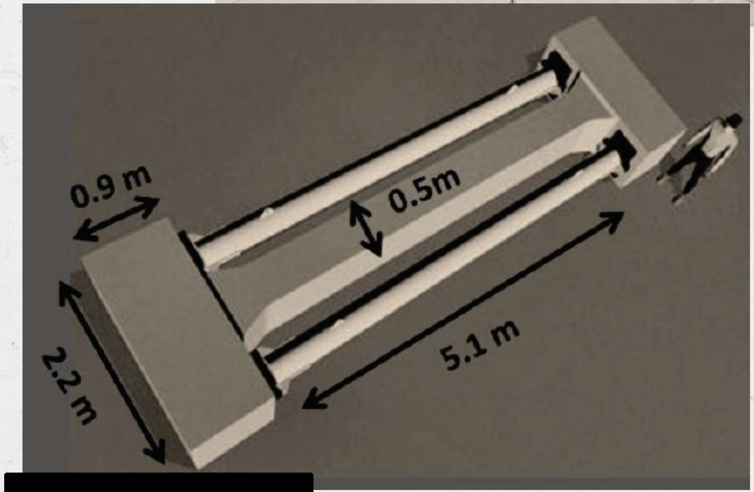


Presentation scope

- Simulation of the large beam RG8 (restrained shrinkage)
- Highlight the modelling and parameter estimation strategies
- Focus on ‘blind stage’ and comparison with actual monitoring

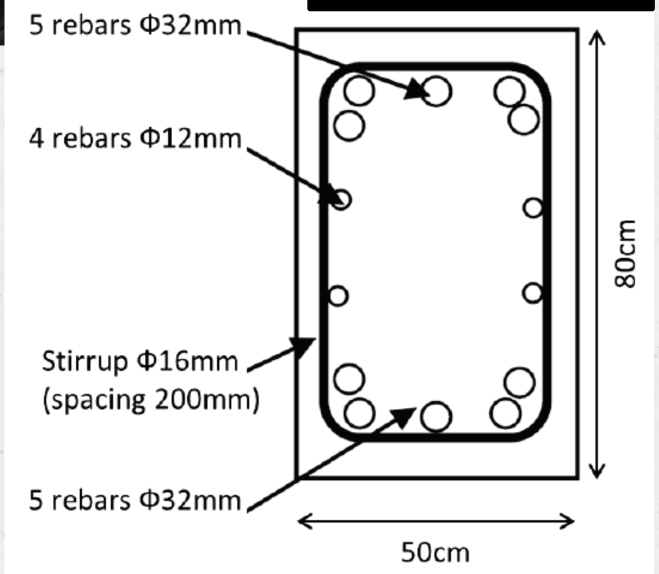
Overview of RG8

Photo



Dimensions

Reinforcement



Significant data on material properties and environmental conditions

Modelling approach

- Thermo-mechanical analyses with FEM (DIANA).
- **Strict compliance** to the material properties/characterization provided by the organization.

Thermal model

- Transient non-linear analysis with 3D brick elements (8 nodes)

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{Q} = \rho c\frac{\partial T}{\partial t}$$

Governing equation

- *k* and ρc mantained constant throughout the entire analysis
- Arrhenius based formulation for cement induced exothermal reactions

$$\dot{Q} = a\ f(\alpha)\ e^{-\frac{E_a}{R\,T}}$$

Reinhardt et al. (1982)

- Convection/radiation coefficient on boundaries (disregarding solar radiation, night cooling and evaporative cooling)

$$q = h_{conv/rad}\left(T_{surf} - T_{env}\right)$$

Modelling approach

Mechanical model

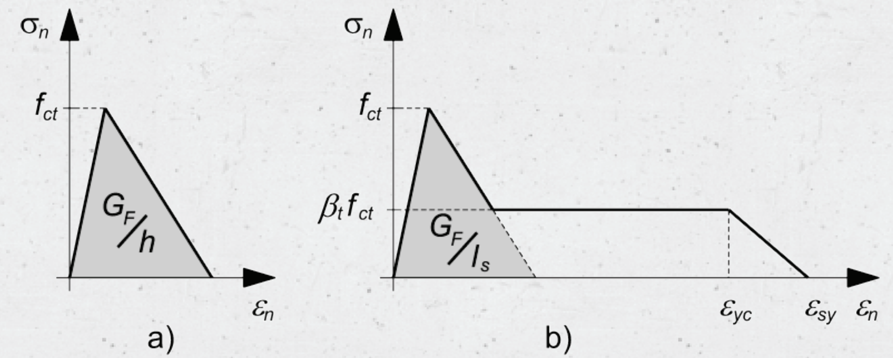
- Transient non-linear analysis with 3D brick elements (20 nodes)
- Maturity dependent properties (equivalent age concept): *E, fct*
- Constant thermal dilation and Poisson's coefficients throughout the analyses
- Creep according to the Double Power Law - DPL (only basic creep simulated)
- Embedded reinforcement (full bond)
- Smeared cracking approach

$$t_{eq} = \int_0^t e^{-\frac{E_a}{R}\left(\frac{1}{T(\tau)} - \frac{1}{T_{ref}}\right)} d\tau$$

Equivalent age concept

$$J(t,t') = \frac{1}{E_0(t')} + \frac{\phi_1}{E_0(t')} (t')^{-m} (t-t')^n$$

Double Power Law



Post-cracking behavior - concrete

Material properties – thermal model

- Heat capacity = 900 J/ºC/Kg (hardened concrete) (CONCRACK)
- Density = 2410 kg/m^3 – from mix composition (CONCRACK)
- Thermal conductivity *k* = 3.28 W/mK – computed with basis on the mix proportions and the thermal conductivity of constituents (Azenha, 2009)
- Strut steel thermal properties: *k* = 54 W/mK; ρc = 3.27×10^6 JK^{-1}m^{-3} (estimated)
- Boundary conditions and transfer coefficients; solar radiation
- Adiabatic temperature rise (CONCRACK)
- Activation energy – computed according to the approach recommended by CONCRACK (Schindler 2004 – ACI Material Journal)

$$E = 22{,}100 \cdot p_{C_3A}^{\,0.30} \cdot p_{C_4AF}^{\,0.25} \cdot \text{Blaine}^{0.35}$$

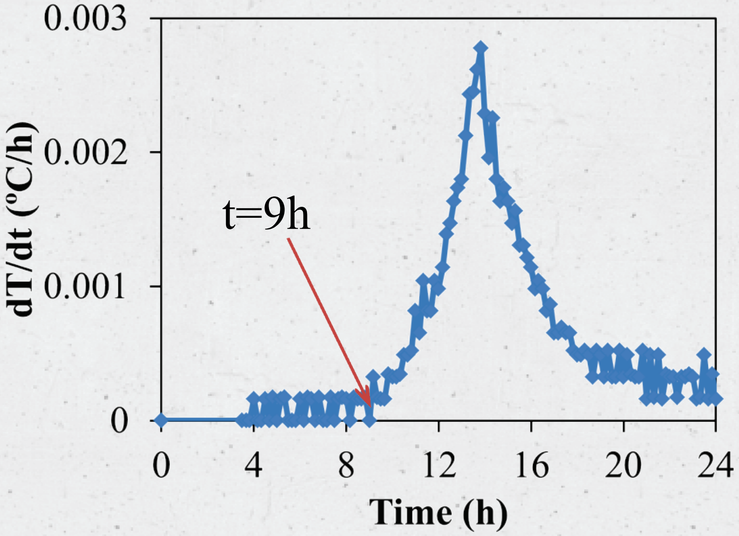
CONCRACK information

$$E = 44600 J / mol$$

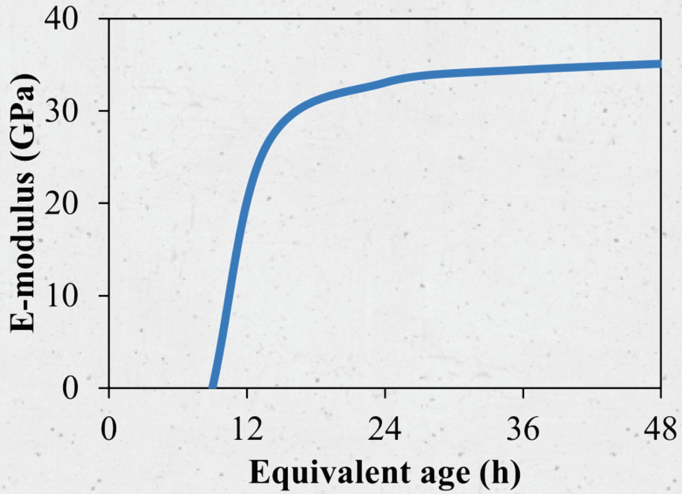
Activation energy used for both hydration heat computation and equivalent age calculations.

Material properties – mechanical model

- Tensile strength – EC2 curve matching data given by CONCRACK
- E-modulus – EC2 curve matching data given by CONCRACK, with an adaptation at early ages as to initiate E-modulus development at approximately 9h age (matching hydration initiation in the adiabatic tests)



dT/dt in the adiabatic test

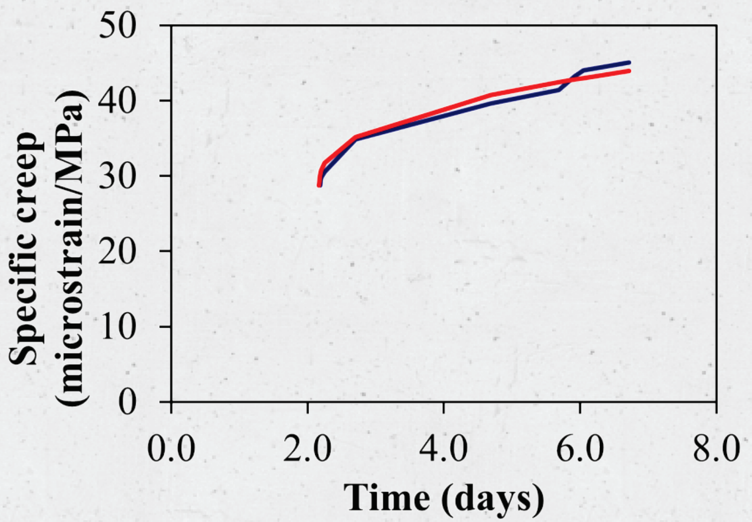


E-modulus evolution

Material properties – mechanical model

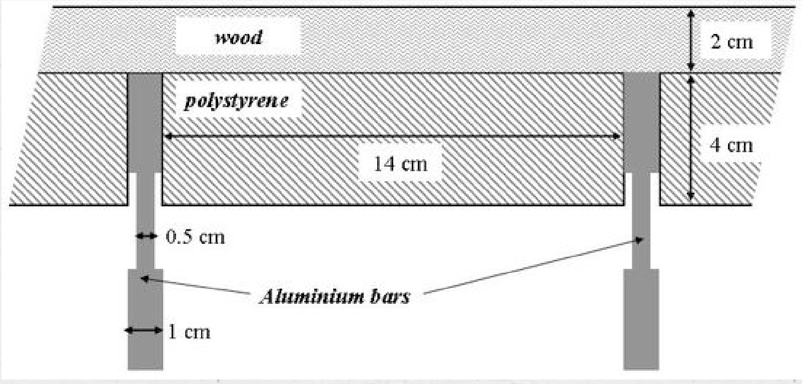
- Thermal dilation coefficient = 12×10^{-6} (CONCRACK)
- Poisson's coefficient = 0.19 (CONCRACK)
- Steel: E=200 GPa; ν=0.3 (CONCRACK) - perfectly plastic behaviour
- Fracture energy G_F = 110 N/m; tension stiffening parameter β_t = 0.4
- DPL Creep parameters adjusted to fit data given by CONCRACK

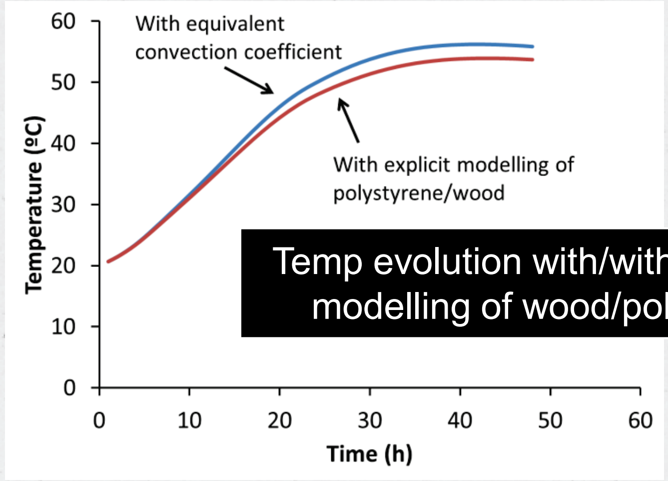
Measured and adjusted creep behaviour



Boundaries and convection/radiation

- Average wind speed v=1.4m/s and env. temperaure (CONCRACK)
- Effect of aluminium bars disregarded
- Recourse to electrical analogy might be arguable due to the large thickness of formwork system -> 2D FEM made for assessment
- Convection/radiation coefficient with radiation contribution linearized according to Azenha (2009); solar radiation neglected
- Convection/radiation coefficient h = 16.3 $Wm^{-2}K^{-1}$ (no formwork) and h =0.75 $Wm^{-2}K^{-1}$ (with formwork)





Temp evolution with/without explicit modelling of wood/polystyrene

Additional aspects

Initial temperature and shrinkage

- Initial temperature 17ºC
- Drying shrinkage as uniform imposed strain with an extent based on the equivalent thickness of the specimen
- Maturity dependent autogeneous shrinkage given by CONCRACK

Time step and load step strategy

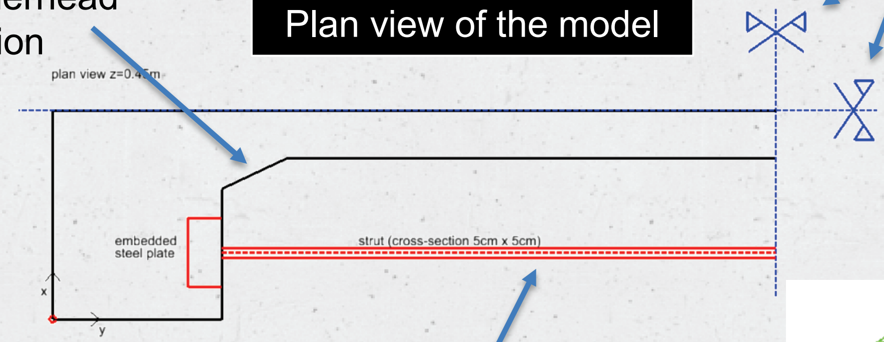
- 60 days of analysis with 1 hour time steps (1438 time steps)
- Load test not simulated

Geometry of the FE model

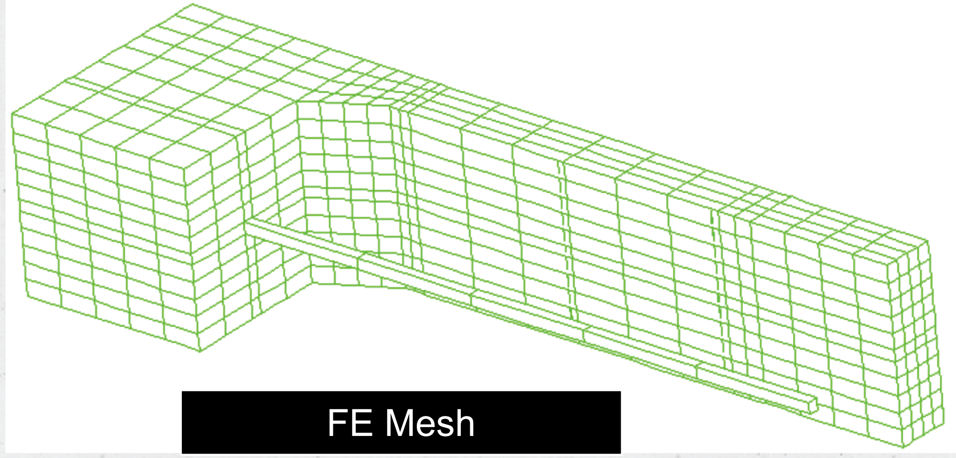
Hammerhead transition

Plan view of the model

1/4th of the specimen

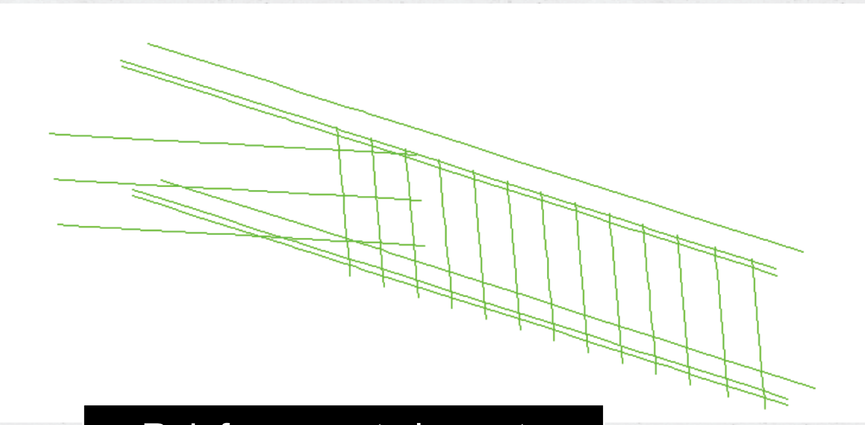


Strut explicitly modelled



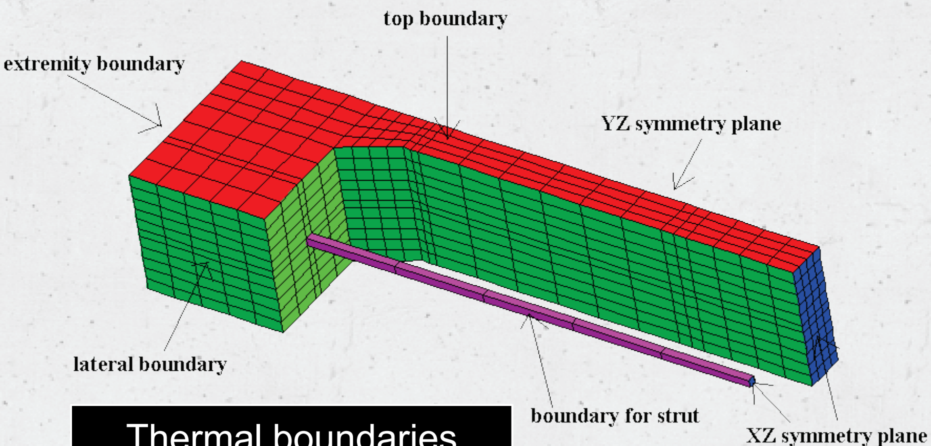
FE Mesh

6700 nodes; 1290 brick elements (20 nodes each)

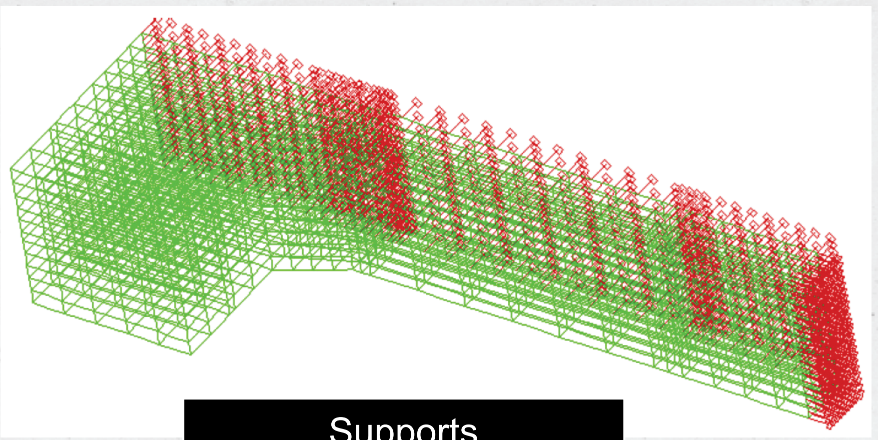


Reinforcement elements

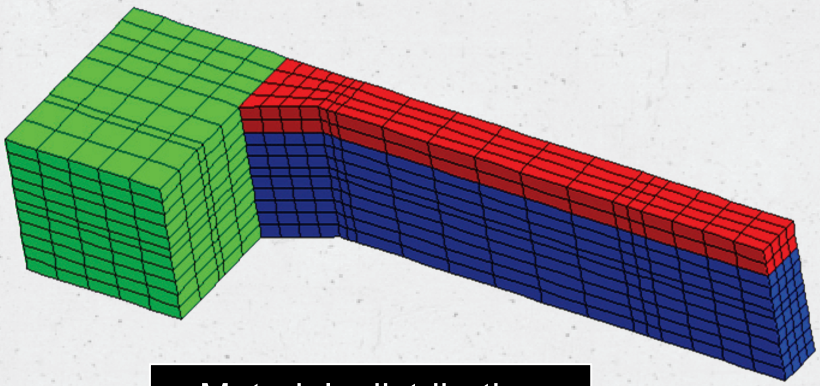
Boundary conditions and material distribution



Thermal boundaries

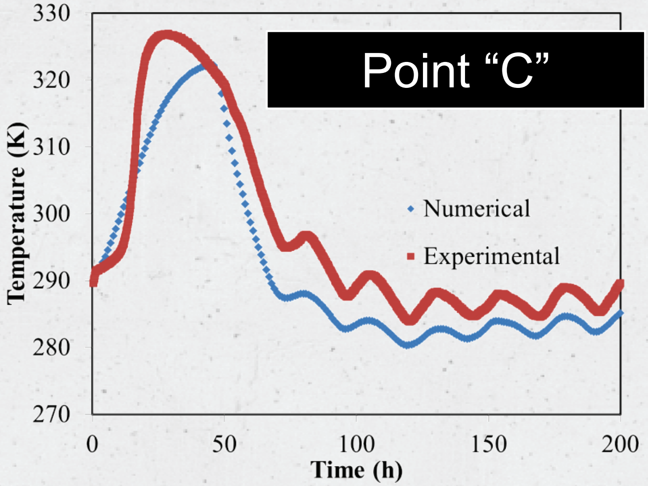


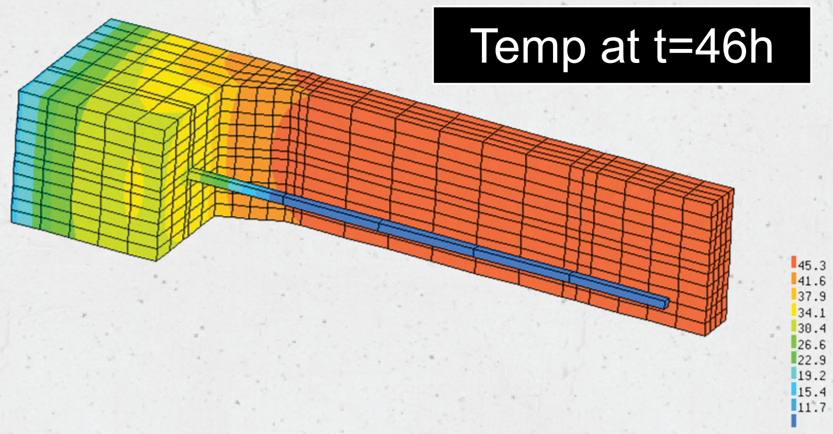
Supports



Materials distribution

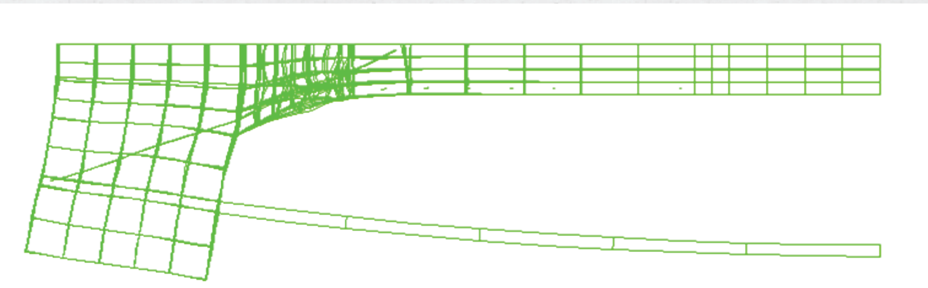
Results of the thermal model



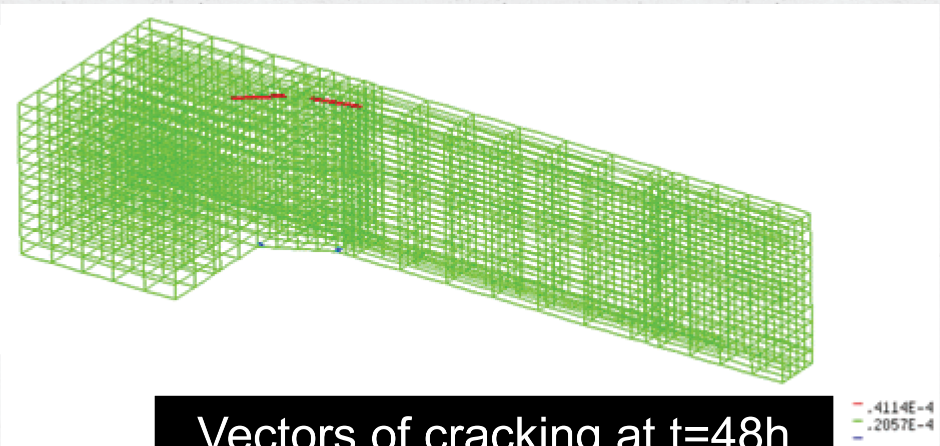


- Peak temperature underestimated 5K; kinetics problems -> from adiabatic temp. rise?
- Temperature less uniform than predicted
- Clear effect of solar radiation
- Average temperature provided by CONCRACK seems under real temperature
- Satisfactory results in view of simplifications (solar radiation, night cooling, electrical resistance analogy…)

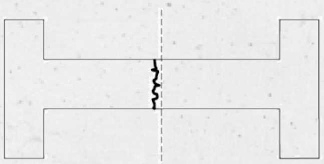
Results of the mechanical model



Deformed shape at t=48h

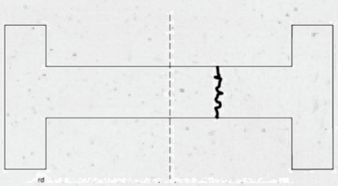


Vectors of cracking at t=48h

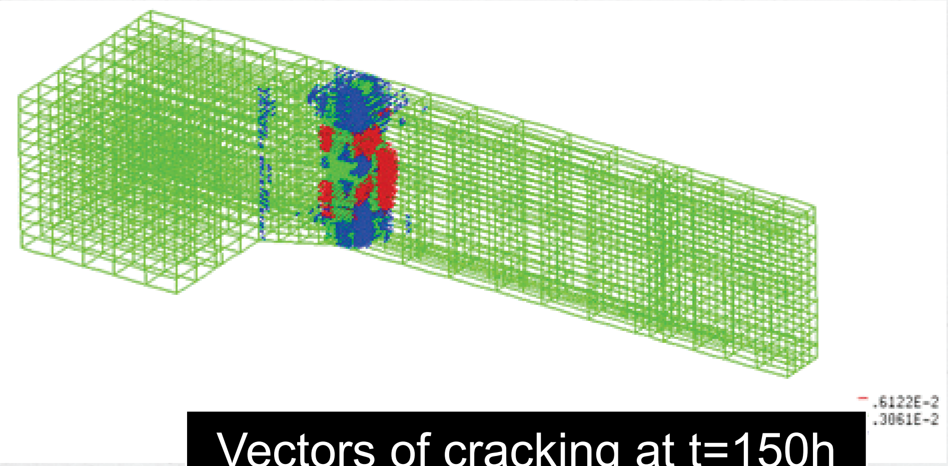


1st crack – 75h

2nd crack – 169h

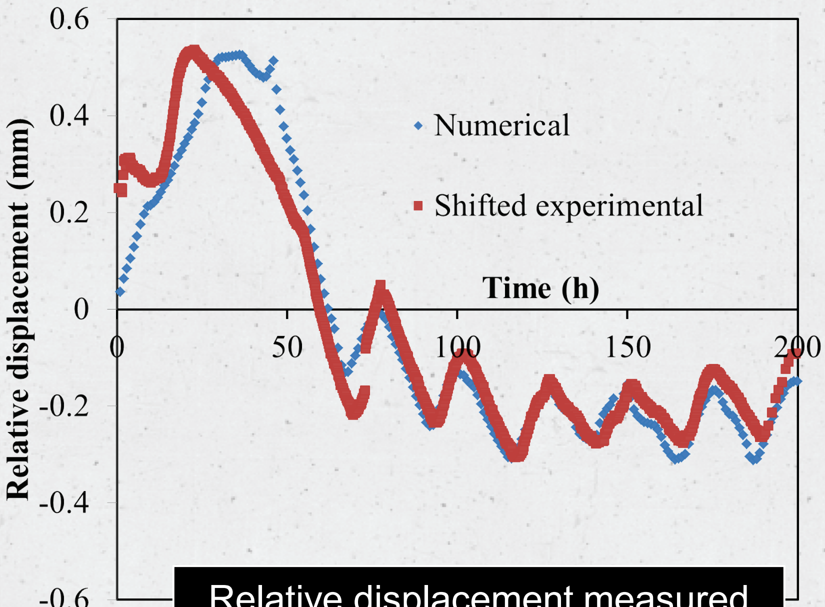


3rd crack – 242h



Vectors of cracking at t=150h

Results of the mechanical model



Relative displacement measured the central region

- Difference in instant of peak displacement related to the temperature calculation
- Post-peak displacements (>48h) correctly simulated
- Pre-peak displacements with simulation innacuracies due to:
  - Prolonged dormant period (not present in simulation)
  - Thermal Dilation Coefficient?
  - Early creep?
  - Monitoring issues?

Conclusions

- Participation of FEUP/UMinho team in Concrack presented.
- Relevance of sound parameter choice and characterization.
- Problems with the temperature field predictions – adiabatic temperature?
- Through cracking well predicted at a later instant than observed experimentally.
- Characterization of concrete and RG8 prepared with the same concrete mix but at different batches -> problem?
- Hottest topic: early viscoelastic behaviour and its validation.
- Overall good performance for a blind stage

Lessons learned for future experiences, particularly in the scope of COST TU1404!

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LESSONS LEARNED FROM IN-SITU MEASUREMENTS IN HARDENING CONCRETE MEMBERS

Dirk Schlicke - Graz University of Technology, Austria

S C I E N C E ▪ P A S S I O N ▪ T E C H N O L O G Y

Outline

- In-situ measuring system for hardening concrete members
- Measuring programs and application examples
- Detected structural behavior
  - Ground slabs
  - Walls on foundations
- Lessons learned
- Outlook

Measuring system

- In-situ measurements

thermocouples in several material points for ΔT

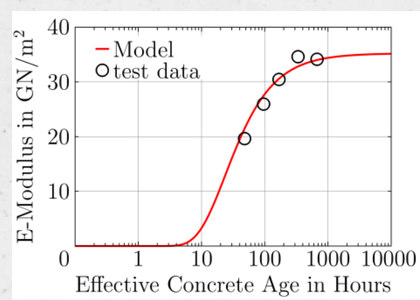
$$\alpha_T \cdot \Delta T + \varepsilon_{cs} + \varepsilon_{cc} = \frac{\Delta l}{l} - \frac{\sigma_c}{E(t)}$$

vibrating wire for (almost) measurement of σ_c / $E(t)$

stressmeter for direct measurement of σ_c

- Accompanying measurements for computational verification

ambient temperature and solar radiation

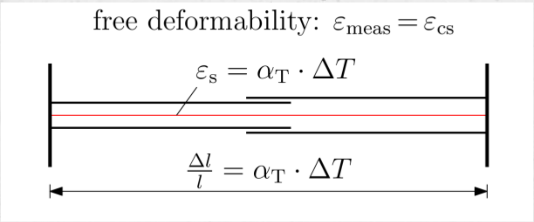


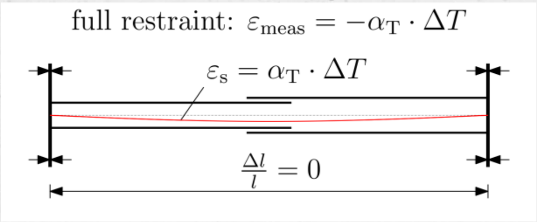
evolution of stiffness $E(t)$

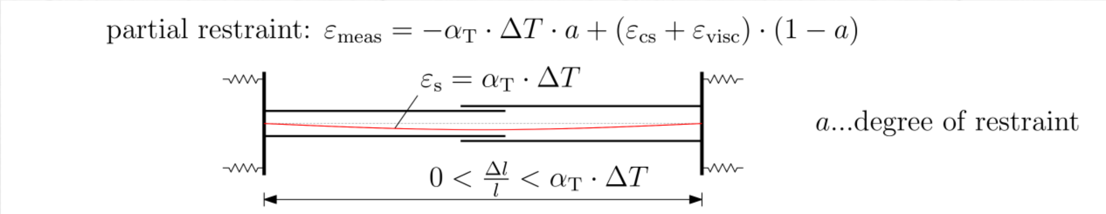
quasi-adiabatic hydration heat release ΔT_{adi}

Measuring system

- General functionality of vibrating wires







no recording of relaxation in the concrete

no recording of restrained shrinkage

no recording of influence of stiffness evolution

$$\Delta\varepsilon_{real}(t_i) = \Delta\varepsilon_{meas}(t_i) + \alpha_T \cdot \Delta T(t_i)$$

$$\Delta\sigma_c(t_i) = \left\lfloor \Delta\varepsilon_{meas}(t_i) - \Delta\varepsilon_{cs}(t_i, t_{i-1}) - \sum_{k=0}^{i-1} \Delta\varepsilon_{crp,k}(t_i, t_{i-1}) \right\rfloor \cdot E_c(t_i)$$

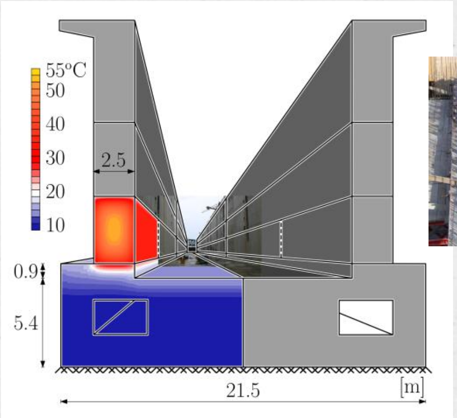
- Compatibility check / validation of determined stresses with direct stress measurements

 vs. 

Measuring programs with direct involvement

Ground slab power plant 'Boxberg', h_P = 3.8 m

Ground slab and chamber wall 'Sluice Sülfeld'

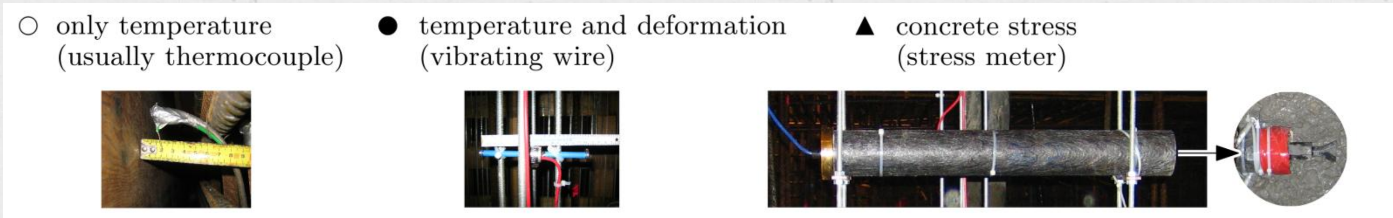


d_W = 2.5 m

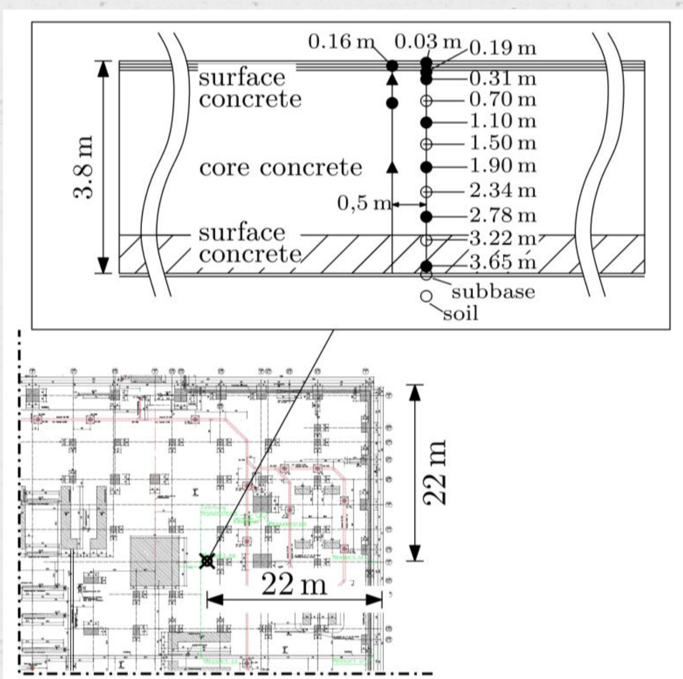
h_P = 5.4 m

Cooling tower shell 'Hamm Westfalen', d_W = 0.3 m

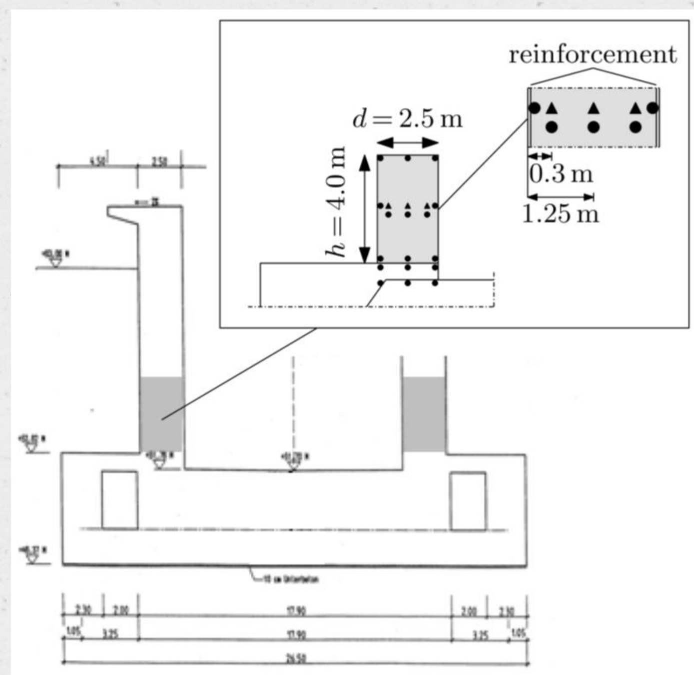
Application examples



Ground slab power plant ‘Boxberg’



Chamber wall ’Sluice Sülfeld‘

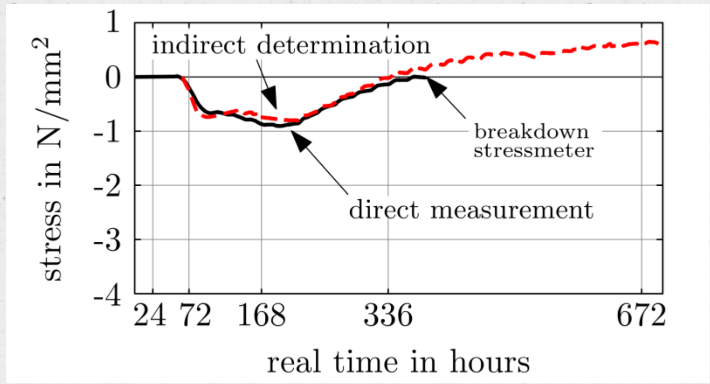


Application examples

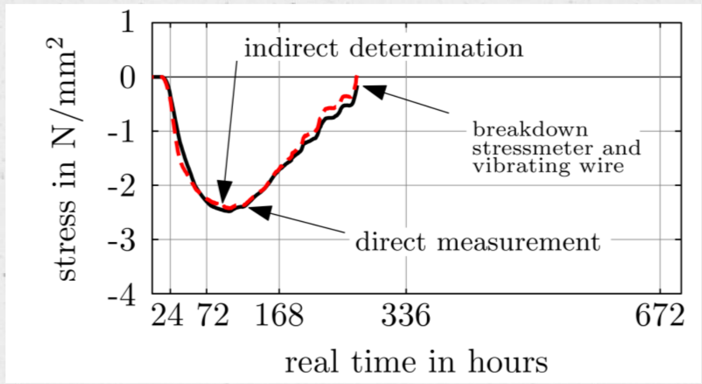
- Compatibility check

vs.

Ground slab power plant ‘Boxberg’



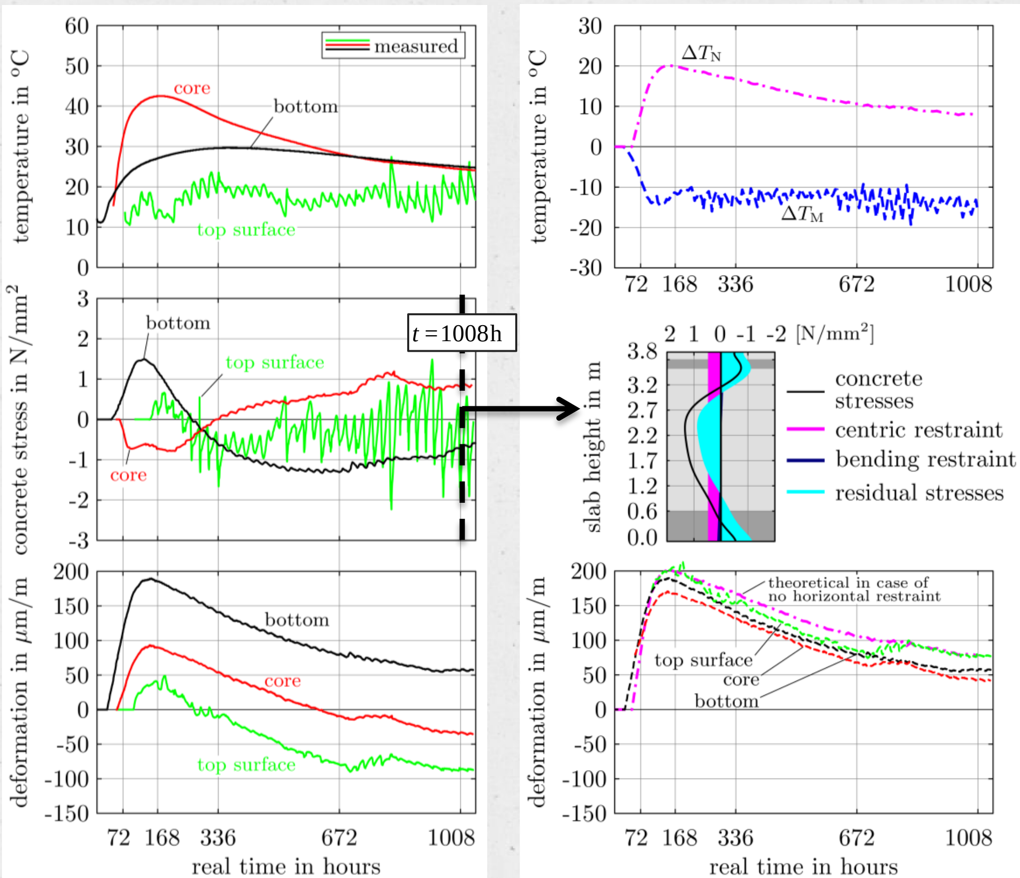
Chamber wall ’Sluice Sülfeld‘



- In both cases the point in the middle of the cross section is shown

Detected structural behavior

- Ground slabs / ground slab power plant ‘Boxberg’



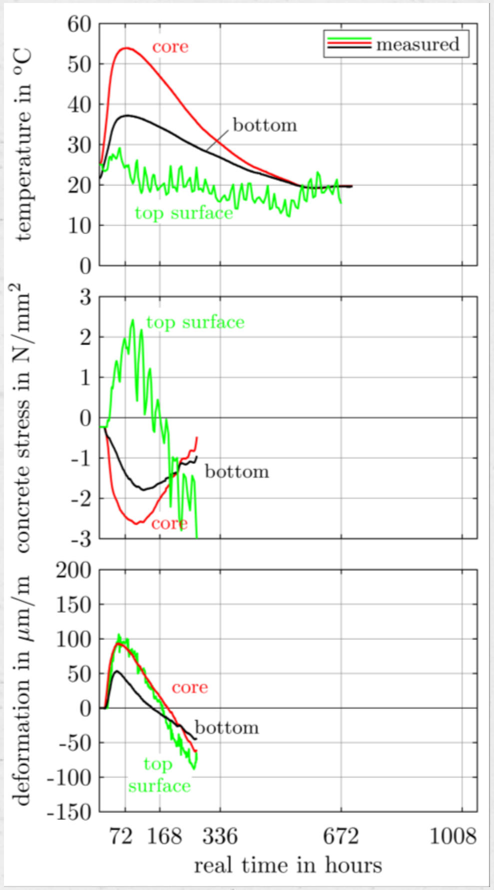
- high uniformly distributed temperature field change (ΔT_N)
- high temperature gradient due to temperature history of bottom side (ΔT_M)

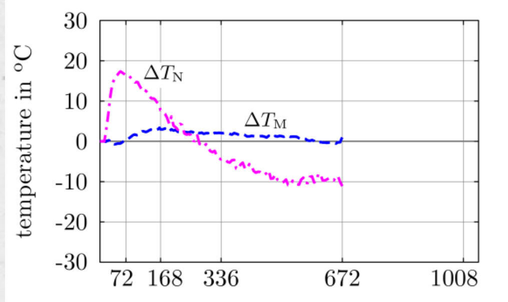
- disproportional small centric restraint
- disappearing bending restraint with approaching of temperature equalization
- considerable residual stresses
- early tensile stressing at bottom due to long lasting casting with retarded layers

- free deformation reaches almost $\alpha_T \cdot \Delta T_N$
- no curvature = 100 % bending restraint
- plane cross section = residual stresses

Detected structural behavior

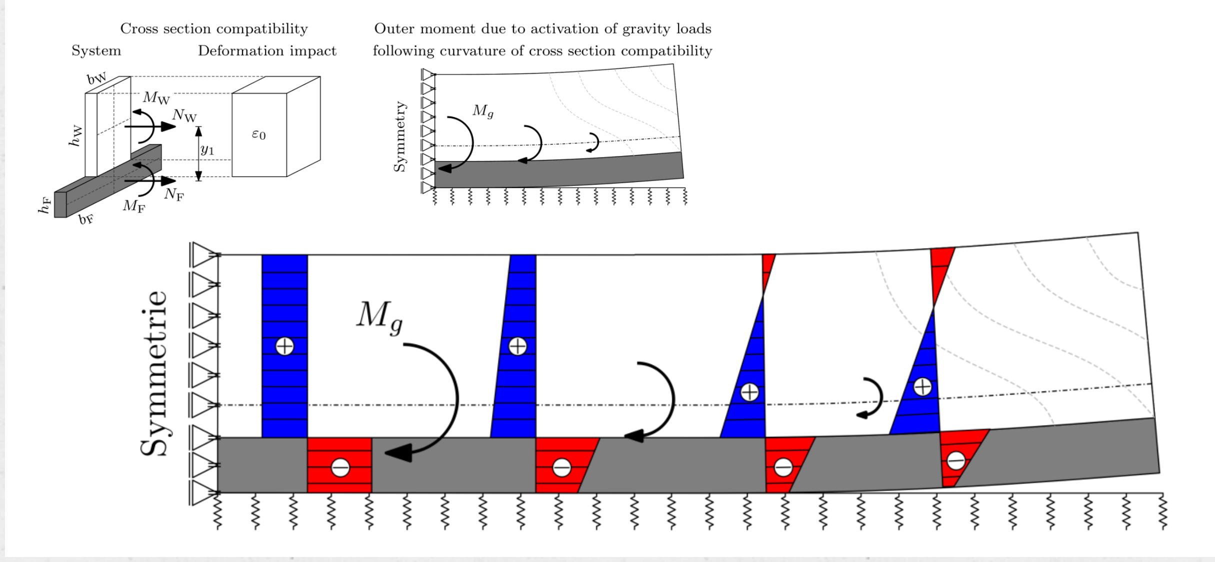
- Walls on foundations / chamber wall 'Sluice Sülfeld'





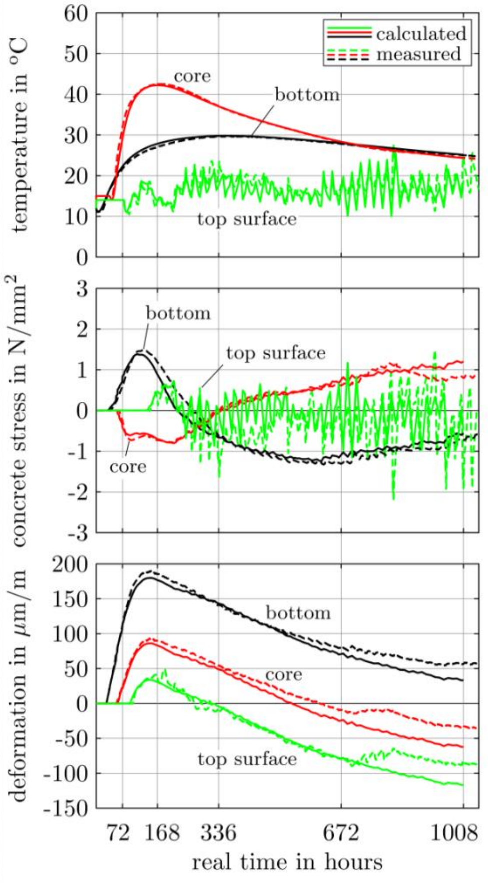
- high uniformly distributed temperature field change (ΔT_N)
- negligible temperature gradient ΔT_M

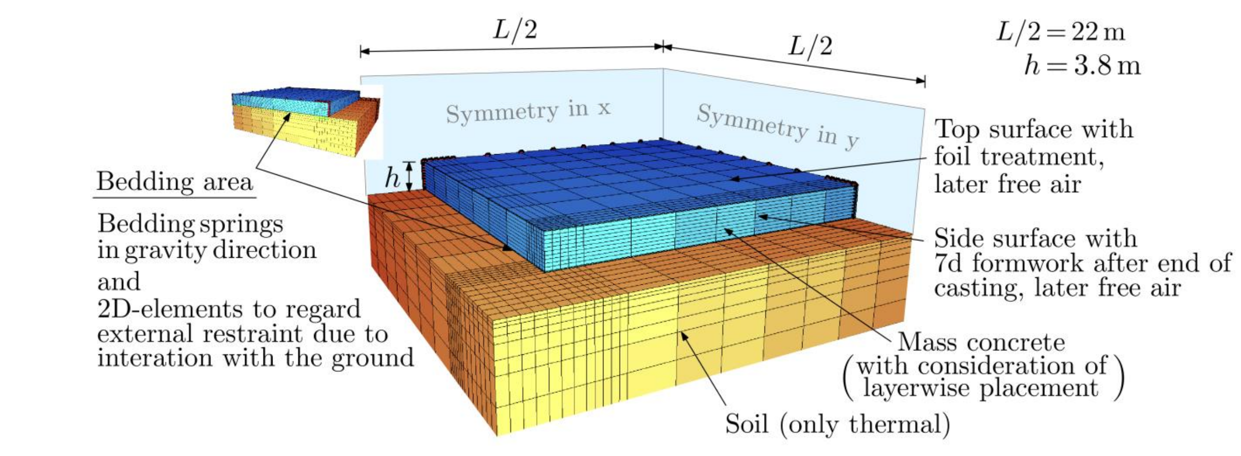
- centric restraint according to ratio of axial stiffness and gravity load ativation



Recalculation with 3D FEM

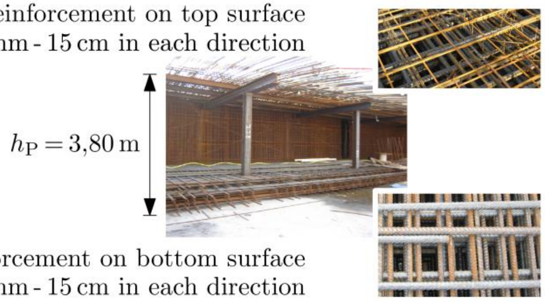
- Ground slabs / ground slab power plant 'Boxberg'





<u>Influence of heavy horizontal reinforcement layers</u>

horizontal reinforcement on top surface
4 layers ⌀ 28 mm - 15 cm in each direction



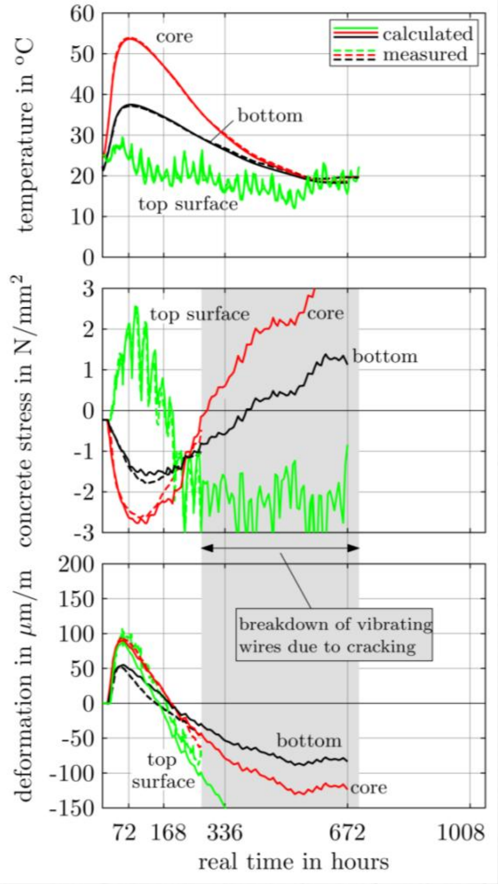
horizontal reinforcement on bottom surface
10 layers ⌀ 28 mm - 15 cm in each direction

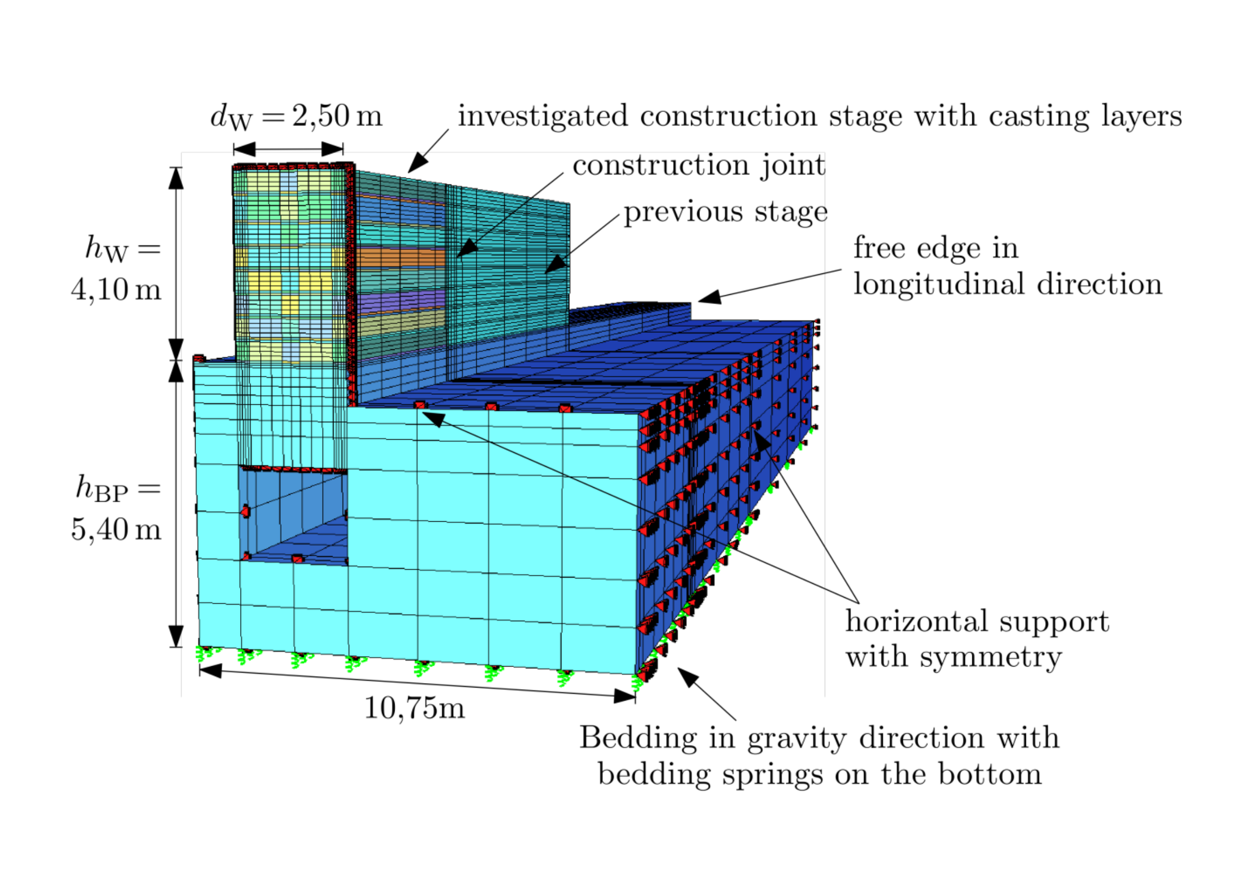
<u>thermal effects:</u>
- increased conductivity
- decreased heat development

<u>mechanical effects:</u>
- increased stiffness
- local shrinkage restraint

Recalculation with 3D FEM

- Walls on foundations / chamber wall 'Sluice Sülfeld'





Lessons learned

- In-situ measurements and data interpretation
  - Reliable material model is needed to interpret results of vibrating wires
  - Stressmeters are viable for stress history as long as the observed material point is under compression
  - Compatibility check of measurement data is indispensable
- 3D FEM Recalculation
  - Heat storage effect of subsoil
  - Realistic consideration of gravity load activation with bedding springs
  - Viable material model
  - Consideration of casting process
  - Consideration of heavy reinforcement layers

Lessons learned

- Structural behavior
  - Ground slabs on standard subsoil: bending restraint is decisive / centric restraint becomes negligible for ground slabs with increasing height
  - Walls: centric restraint is decisive but depends considerably on the gravity load activation according to the length-heigth-ratio

- Efficient crack width control
  - requires consideration of real member behavior

Schlicke, D. and Tue, N. V. (2015),

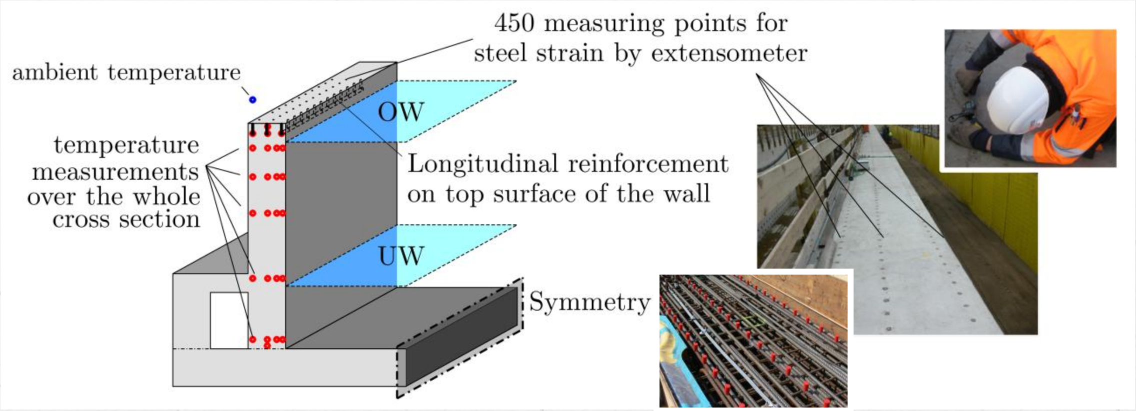
Minimum reinforcement for crack width control in restrained concrete members considering the deformation compatibility.

Structural Concrete, 16: 221 - 232. doi: 10.1002/suco.201400058

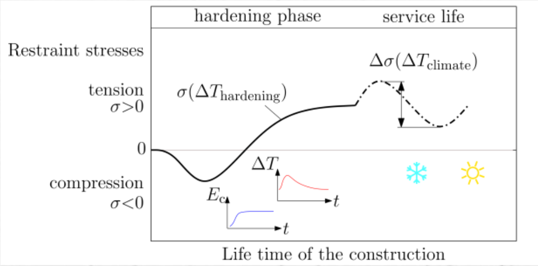
Outlook

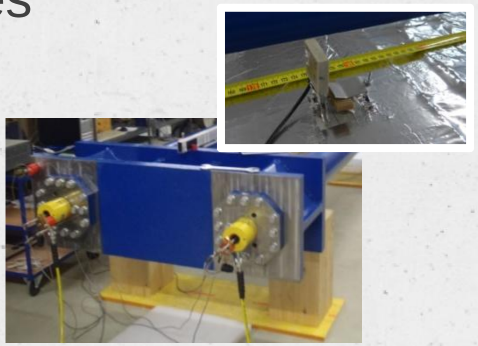
- Service life monitoring of monolithic structures

260 m long jointless sluice 'Wusterwitz'



- Experimental simulation of restrained RC structures





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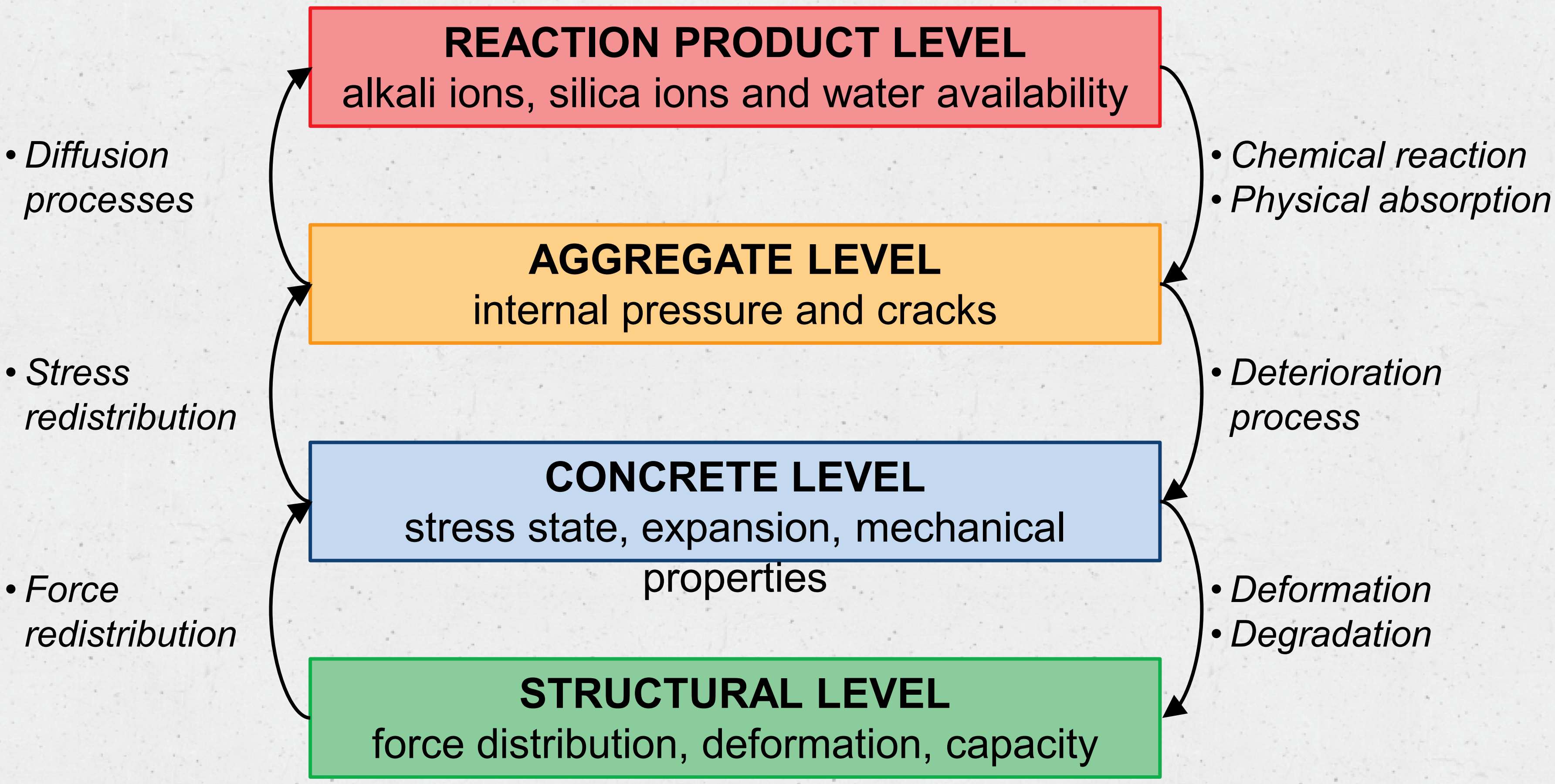
The Deteriorating Impact of Alkali-Silica Reaction in Concrete

Max A.N. Hendriks – Delft University of Technology, Netherlands
& Norwegian University of science and technology, Norway
Rita Esposito – Delft University of Technology, Netherlands

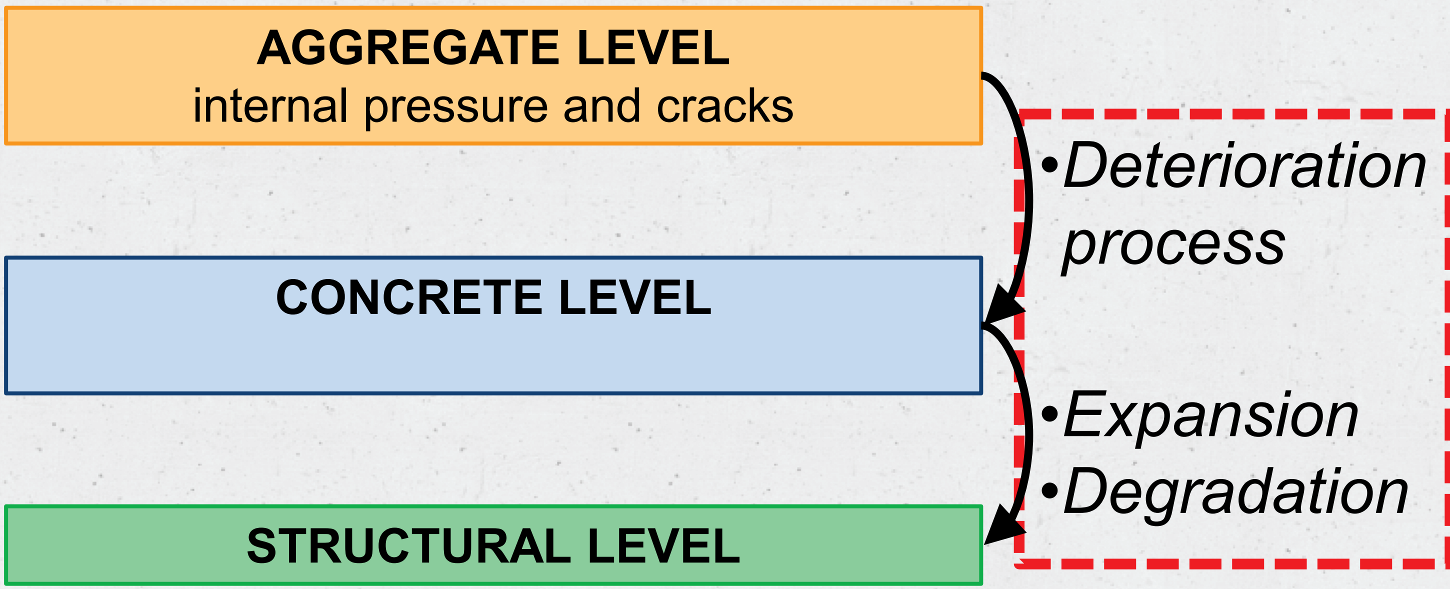
TU Delft NTNU STW Rijkswaterstaat Ministerie van Infrastructuur en Milieu

Alkali-Silica Reaction in Concrete: Multiple scales



Focus of this presentation

Relation between ASR expansion & Degradation of concrete properties



The Deteriorating Impact of Alkali-Silica Reaction in Concrete

Expansion vs. Mechanical Properties

Free Expansion Experiments

- Testing «Nautesund Concrete»
- Statistical analysis of literature data

Multiscale Material Modeling

- Micro-poro-fracture mechanics
- Analytical homogenization

The Deteriorating Impact of Alkali-Silica Reaction in Concrete

Expansion vs. Mechanical Properties

Free Expansion Experiments

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- Statistical analysis of literature data

Multiscale Material Modeling

- Micro-poro-fracture mechanics
- Analytical homogenization

ASR-induced Mechanical Degradation of Concrete

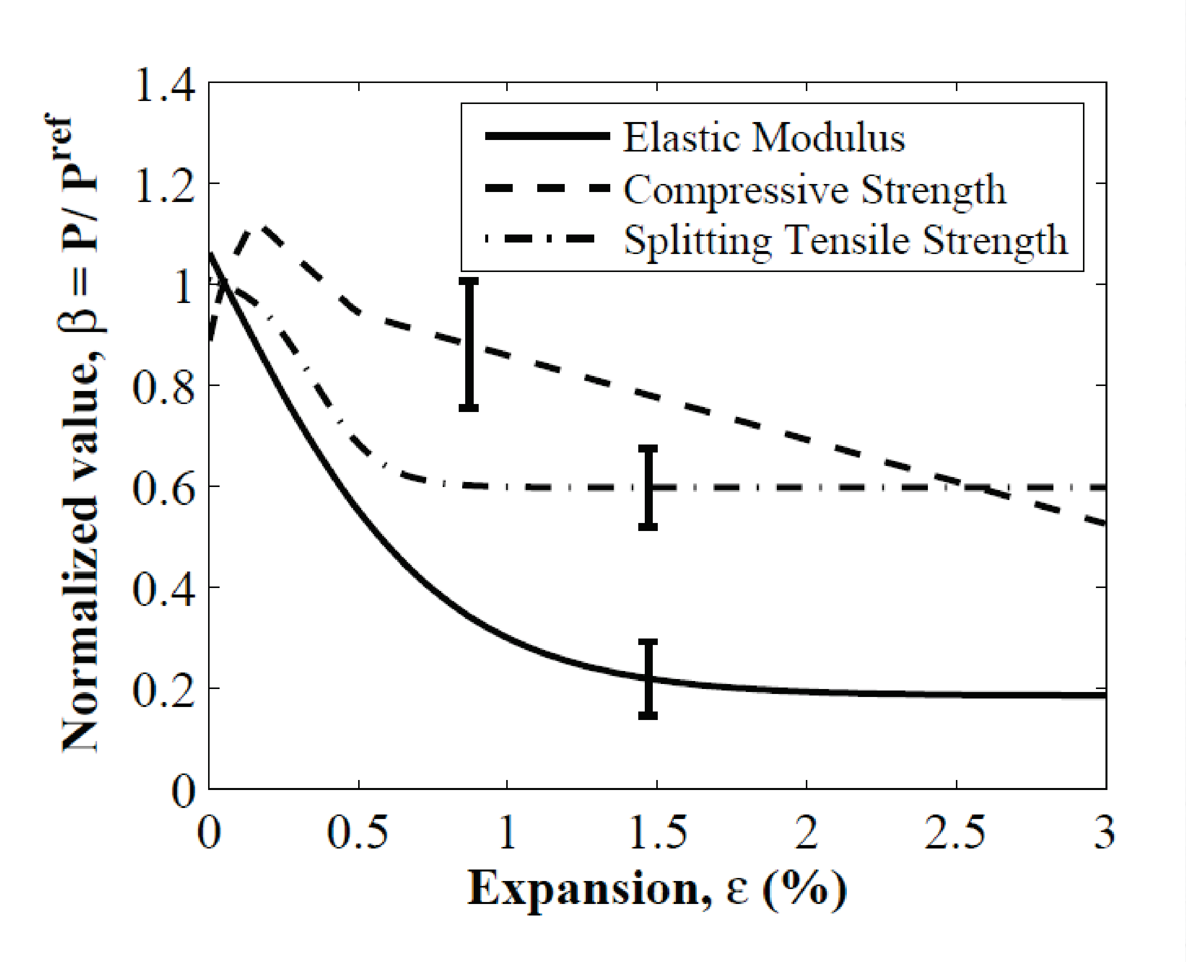
- Mixes with 2 type of aggregates:
  - Norwegian crushed aggregates
  - Dutch natural aggregates
- Testing:
  - Expansion
  - Mechanical properties (elastic modulus and strengths)
- Statistical analysis
  - Evolution of mechanical properties as a function of the expansion

Statistical analysis

- Literature data from **12 authors**:
  - Young's modulus: 9 authors
  - Compressive strength: 10 authors
  - Tensile strength: 7 authors

- The **mechanical properties** have been **normalized** with respect to their value at expansion equal to 0.05%

Mechanical properties vs. Expansion



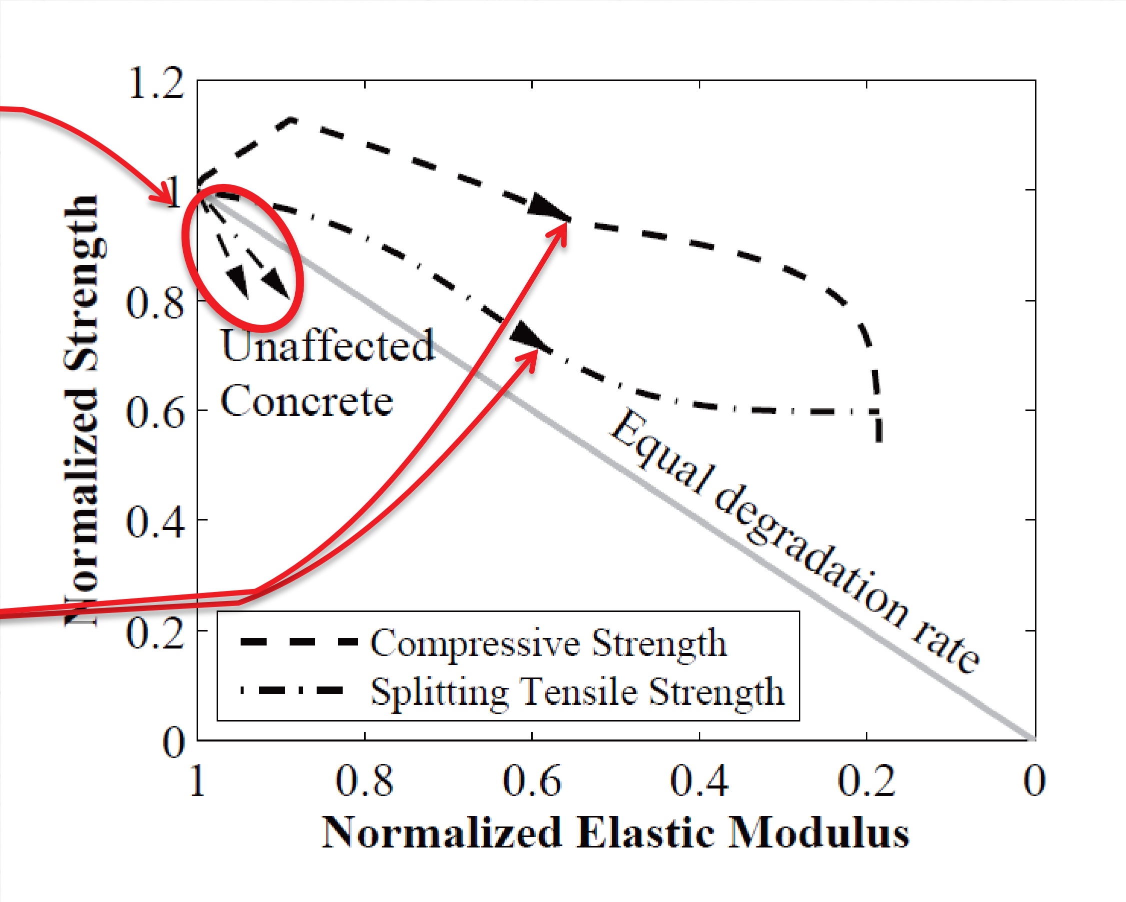
- **Statistical relevant relations between properties and expansion**
- **Elastic modulus best indicator**
- All the properties degradates with a **different rate**

INFLUENCE OF THE ALKALI-SILICA REACTION ON THE MECHANICAL DEGRADATION OF CONCRETE,
Rita Esposito, Caner Anaç, Max A.N. Hendriks, Oguzhan Çopuroglu, Accepted for ASCE's Journal of Materials in Civil Engineering

Strengths vs. Stiffness

The standardized relations between stiffness and strenght properties for sound concrete

are not applicable for ASR affected concrete



IMPORTANT for structural assessment

The Deteriorating Impact of Alkali-Silica Reaction in Concrete

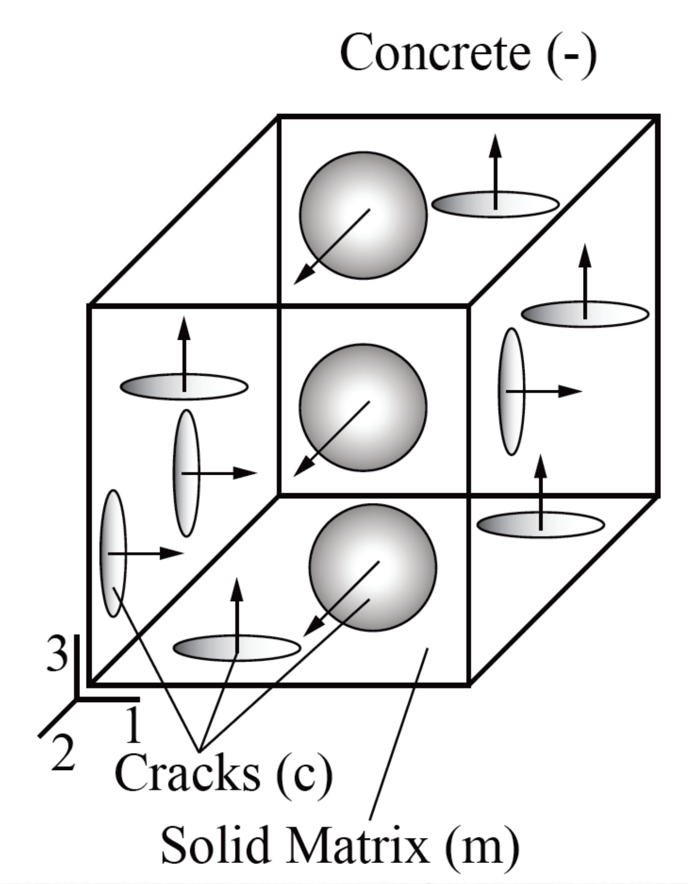
Expansion vs. Mechanical Properties

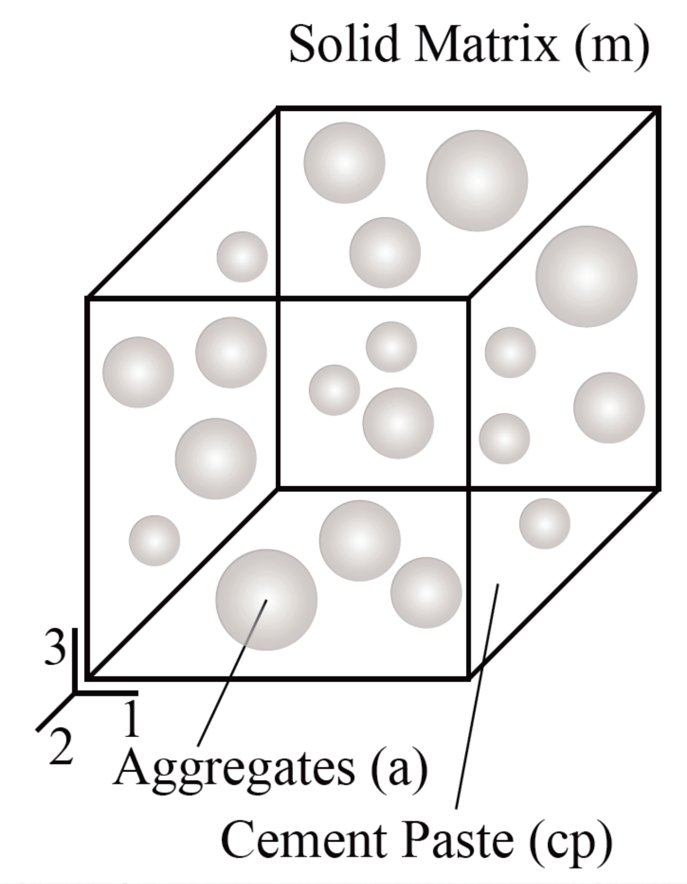
Free Expansion Experiments		Multiscale Material Modeling	
Testing «Nautesund Concrete»	Statistical analysis of literature data	Micro-poro-fracture mechanics	Analytical homogenization

Multiscale Material Model

- From aggregate to concrete level
- **Poro-mechanics** → Swelling of ASR gel = internal pressure
- **Analytical Homogenization** → Concrete properties retrieved by properties of its constituents
- **Linear fracture mechanics** → Damage propagation

Structure of concrete





State Equations

- Poro-mechanics Theory
  - Effect of external mechanical load (**E**)
  - Internal pressure (P)

$$\boldsymbol{\Sigma} = \mathbb{C} : \boldsymbol{E} - \boldsymbol{B} P$$

$$\Phi - \Phi_{in} = \frac{P}{N} + \boldsymbol{B} : \boldsymbol{E}$$

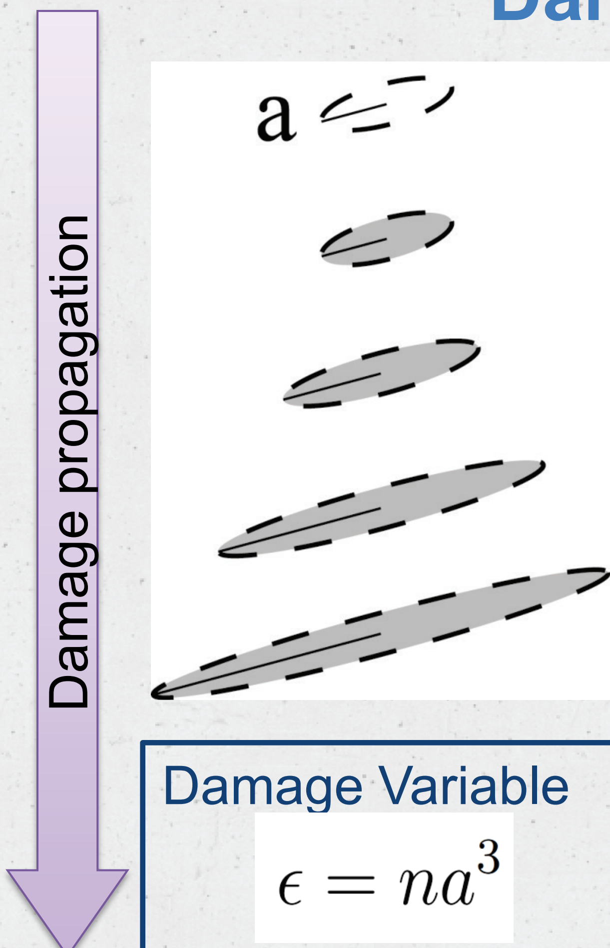
Overall drained stiffness

Biot tensor

Biot modulus

Microporomechanis, 2006

Damage Criterion



- Based on Linear Fracture Mechanics Theory
- Thermodynamic balance

Damage Variable

$$\epsilon = na^3$$

Crack propagation

$$G(\boldsymbol{E}, P, \in, \square) \geq G_c(\in, G_f)$$

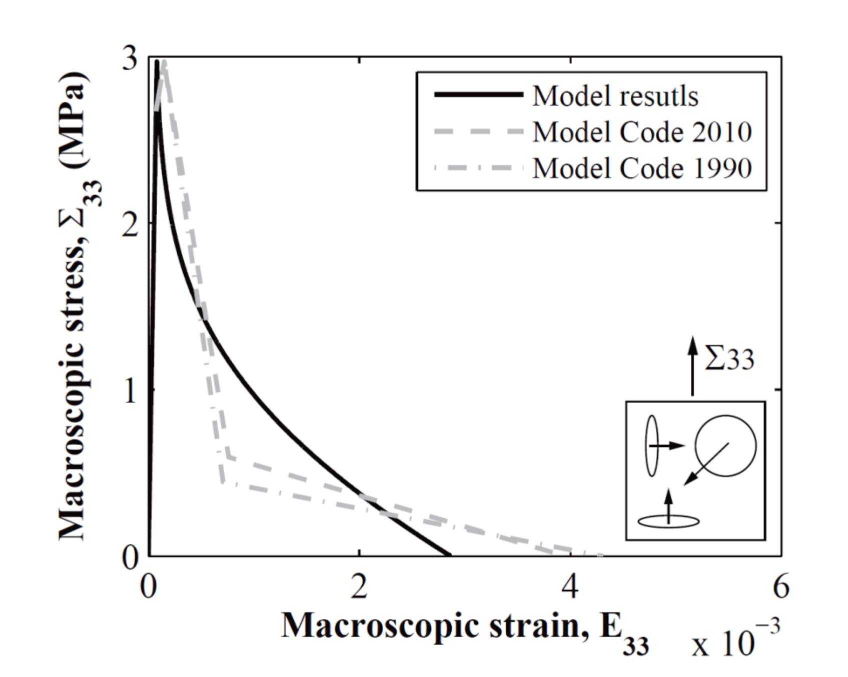
- G → Energy release rate
- G_c → Critical energy relese rate
- G_f → Micro Fracture Energy

Model's assumptions

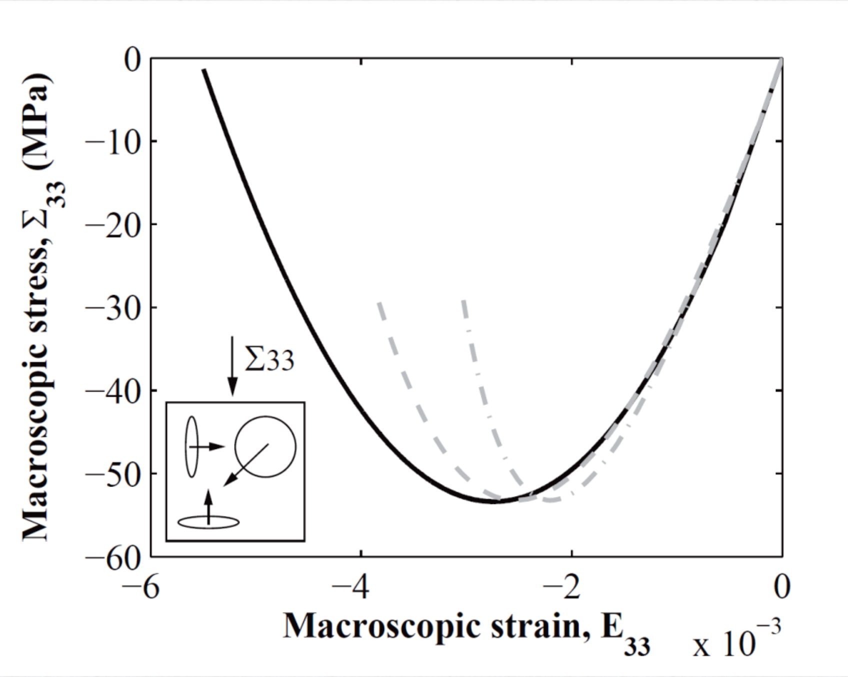
- ASR gel swelling gives **Internal pressure** → pressure controlled model
- Properties of solid matrix are constant during damage → **No distinction in damage location**
- Solid matrix is a **linear elastic material**
- The damage propagation is related to the **dissipated energy**

Unaffected concrete

Tensile Behaviour



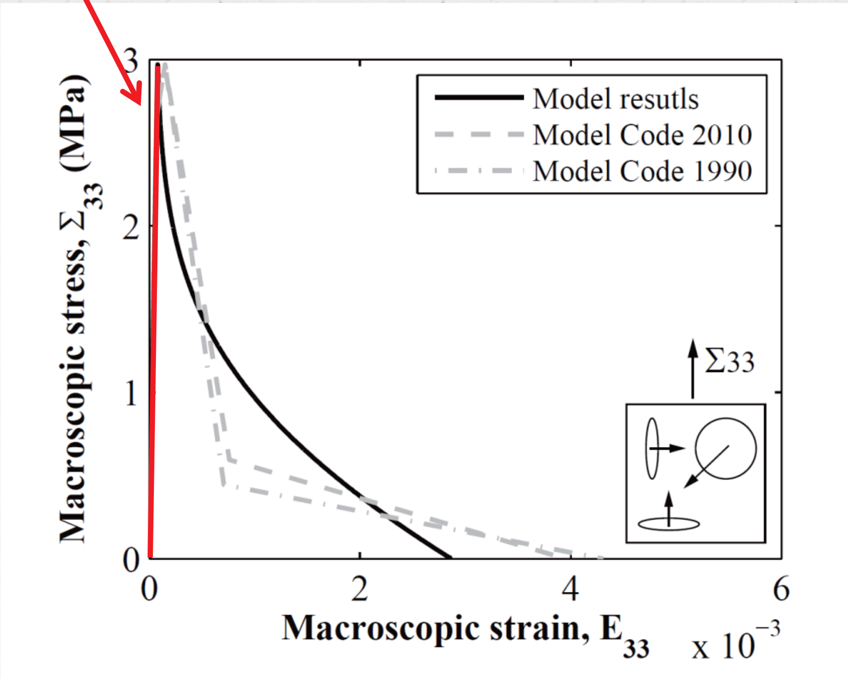
Compressive Behaviour



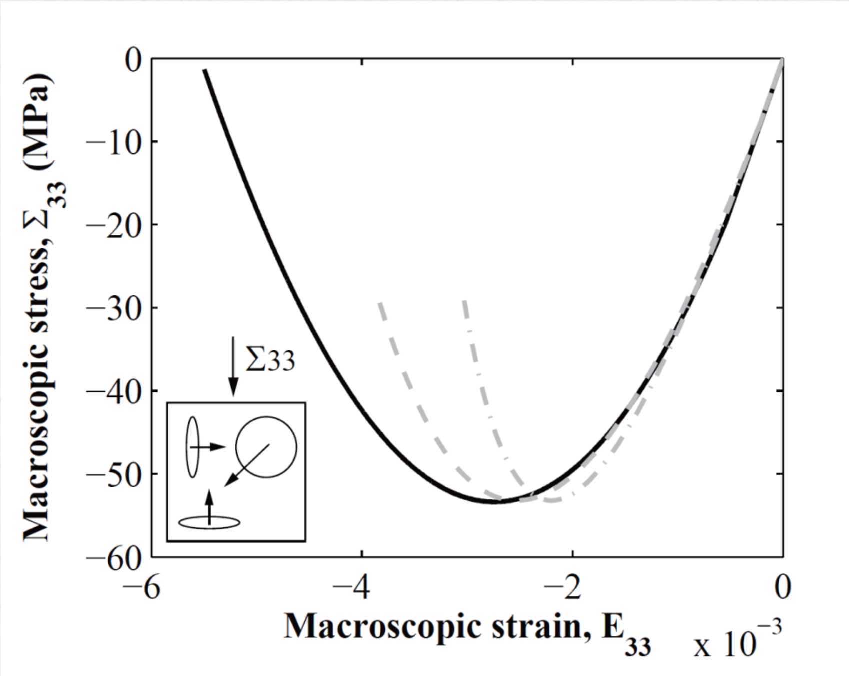
Unaffected concrete - Uniaxial loading

Calibrated for the linear regime in tension,

Tensile Behaviour

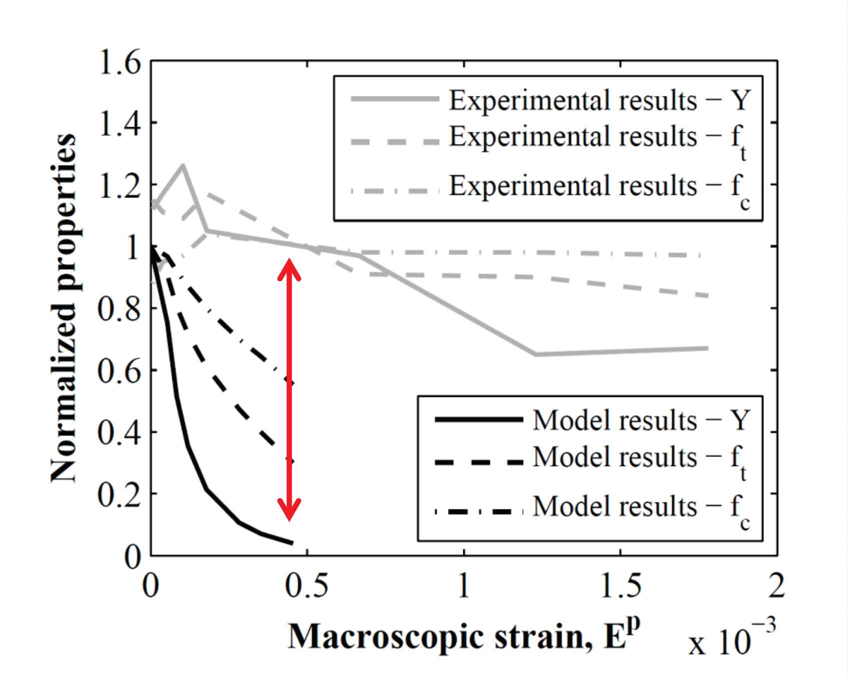


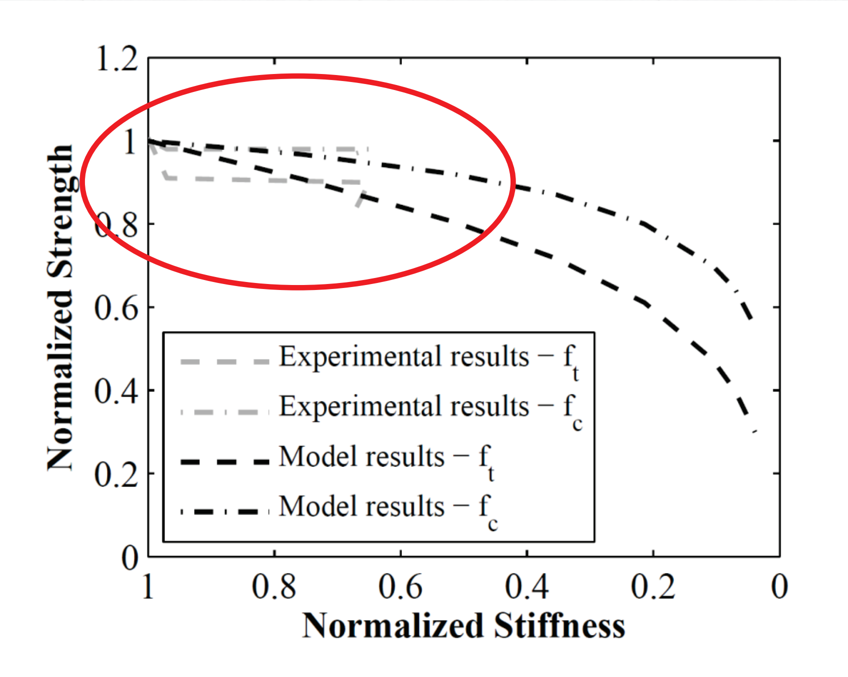
Compressive Behaviour



the model simulates the softening and hardening branches in tension and compression

ASR-affected concrete: comparison with experiments





- The ASR expansion strains are under-predicted
- The relation between the mechanical properties is resembled well

The Deteriorating Impact of Alkali-Silica Reaction in Concrete

1. Experimentally, we observe statistical relevant relations **between ASR expansion and ASR degradation**

   - **In absence of permanent deformations,**
   - **the model underestimates the expansion.**

2. The known relationships **between strength and stiffness** properties of sound concrete do not apply for ASR affected concrete

   - **Well simulated by the model**

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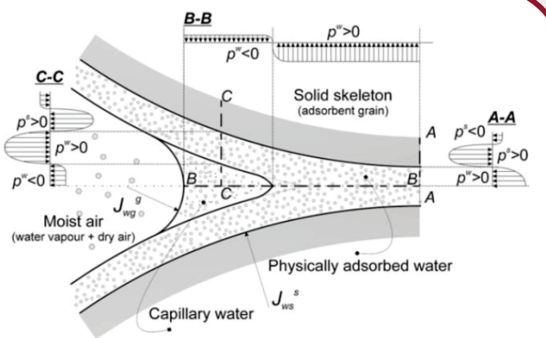
MODELING OF CONCRETE DURABILITY WITH POROMECHANICAL APPROACH

Francesco Pesavento - University of Padova, Italy
Bernhard Schrefler – University of Padova, Italy
Luciano Simoni – University of Padova, Italy
Dariusz Gawin – Tech. University of Lodz, Poland
Mateusz Wyrzykowski – EMPA, Switzerland

Mathematical Model:
Micro → Macro-description in averaging theories



LOCAL FORMULATION

(MICRO-SCALE, DETAIL OF THE REV)

Upscaling

System of governing equations:

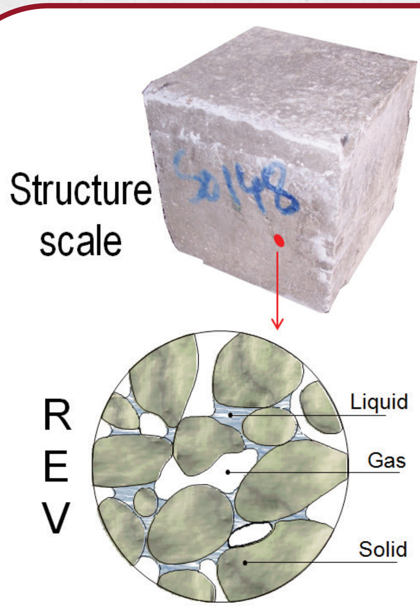
-Mass balance equations of the phases;

-Linear momentum balance equations;

-Mass balance equations of the species.

MACROSCOPIC FORMULATION

Thermodynamically Constrained Averaging Theory *(Gray & Miller, 2005)*



i) The Representative Elementary Volume (REV) at microscopic level must be large enough so that averages of properties are independent of the sample size.

ii) The REV must contain all phases.

iii) REV represents a point in the macroscopic description: REV must be small enough so that partial derivatives at macroscopic level make sense

Closure relationships

NUMERICAL SOLUTION

FEM (in space)

FDM (in the time domain)

Mathematical Model: Evolution equations

EVOLUTION EQUATIONS:

- ✓ Evolution equation for hydration/dehydration
- ✓ Evolution equation for material damage (work in progress)
- ✓ Evolution equation for thermo-chemical damage
- ✓ **Evolution equation for ASR process**
- ✓ **Evolution equations for freezing/melting processes**
- ✓ **Evolution equation for Leaching**

INTERNAL VARIABLES:

- ✓ Hydration/Dehydration degree – $\wp_{hydr}$
- ✓ Mechanical damage degree – *d*
- ✓ Thermo-Chemical damage degree – *V*
- ✓ **ASR reaction extent – Γ_{ASR}**
- ✓ **Mass of frozen water (i.e. ice) – m_{ice}**
- ✓ **Leaching degree ($\Gamma_{leach}\left[s_{Ca}(t)\right]=\dfrac{s_{Ca}^0-s_{Ca}(t)}{s_{Ca}^0}$)**

Alkali-Silica-Reaction simulation

Existing models and model proposed

- *The **existing models** can be classified essentially into two classes: models which attribute the process progression to the water imbibitions (temperature independent) [1, 2] and models which consider temperature as the main parameter, i.e. ASR is considered as a pure thermally activated process [3, 4].*

- *In the **present model** the ASR is modelled as a two-stage process, involving chemical reactions causing first silica dissolution and then gel formation, [1]. The effect of moisture content on the kinetics of the first process is considered similarly as in [1, 2] and effect of temperature following approach proposed in [3, 4]. It is assumed that the gel formation process causes expansion of the material skeleton and the maximal chemical strain is dependent on the moisture content and to a much lesser extent on the temperature value. The gel is assumed to be in equilibrium with moisture in its pores, hence any variation of relative humidity causes an immediate change of chemical strains, also during decrease of water content.*

① *A. Steffens et al., Aging Approach to Water Effect on Alkali–Silica Reaction Degradation of Structures, Journal of Engineering Mechanics, 129, 50-59, (2003).*

② *F. Bangert et al., Chemo-hygro-mechanical modelling and numerical simulation of concrete deterioration caused by alkali-silica reaction, Int. J. Numer. Anal. Meth. Geomech., 28(78), 689-714, (2004).*

③ *Larive, C. Apports combinés de l'expérimentation et la modélisation à la compréhension de l'alcali-réaction et de ses effets mécaniques, Monograph LPC, 0A28, Laboratoire Central des Ponts et Chaussées, Paris (1998).*

④ *F-J Ulm et al., Thermo-chemo-mechanics of ASR expansion in concrete structures, Journal of Engineering Mechanics, 126(3), 233-242, (2000).*

Model of Silica Alkali Reaction

First stage of the process: evolution of the reaction extent Γ_{ASR}

$$\dot{\Gamma}_{ASR} = \frac{1-\Gamma_{ASR}}{t_r}$$

where (at constant T and S_w):

$$\Gamma_{ASR}(t) = \frac{\varepsilon_{ASR}(t)}{\varepsilon_{ASR,\infty}}$$

$t_r = k_r / A_0$ **is the reaction time (A_0 is the initial chemical affinity and k_r is the kinetic coefficient)**

The chemical affinity is: $A_r(\Gamma_{ASR}) = A_{r0}(1-\Gamma_{ASR})$

❑ ***Ref.: Larive et al,***
Journal of Engineering Mechanics 2000

The reaction time is: $t_r = \tau_r(T, S_w) \cdot \lambda(T, S_w, \Gamma_{ASR})$ where $\lambda(T, S_w, \Gamma_{ASR}) = \frac{1+\exp(-\tau_L / \tau_r)}{\Gamma_{ASR} + \exp(-\tau_L / \tau_r)}$

with

Latency time

$$\tau_L(T, S_w) = \tau_{L0}\left[U_L\left(\frac{1}{T} - \frac{1}{T_0}\right)\right](A_L \cdot S_w + B_L)$$

Influence of saturation level

Characteristic time

$$\tau_r(T, S_w) = \tau_{r0}\left[U_r\left(\frac{1}{T} - \frac{1}{T_0}\right)\right](A_L \cdot S_w + B_L)$$

$\tau_{L0}, \tau_{r0}, A_L, B_L$ are material parameters

Model of Silica Alkali Reaction

Second stage of the process: evolution of ASR strain Σ_{ASR}

$$\dot{\varepsilon}_{ASR}(t) = \frac{\alpha}{\rho^{ASR}} \cdot \dot{m}_{ASR}(t)\mathbf{I}$$

Where $\dot{m}_{ASR}$ is the rate of water mass combination with the gel $\dot{m}_{ASR} \propto \dot{\Gamma}_{ASR}$

α is the chemo-elastic dilatation coefficient;

ρ^{ASR} the density of the formed gel.

- ***Ref.: Pesavento et al**, Comp. Methods in Appl. Mech. and Eng. 2012*

Water Aging

Due to peculiar physico-chemical processes a loss of swelling potential is experimentally observed; this loss can be considered as a sort of "material aging":

$$\dot{\Gamma}_a = \frac{1-\Gamma_a}{t_a}$$

with

Γ_a is the aging process extent;

t_a is the characteristic time of aging.

- ***Ref.: Steffens et al**, Journal of Engineering Mechanics 2003*

The water-gel combination rate is now:

$$\dot{m}_{ASR} = M_{ASR}(S_w)\cdot(1-\Gamma_a)\cdot\dot{\Gamma}_{ASR}$$

in which $M_{ASR}(S_w)$ is the water combination coefficient at saturation level S_w

Modelling ASR: experimental-numerical results comparison

Poyet's experimental tests at constant relative humidity

✓ Material properties as in:

*S. Poyet, Etude de la dégradation des ouvrages en béton atteints de la réaction alcali–silice: approche expérimentale et modélisation numérique multi-échelle des dégradations dans un environnement hydrochemo–mécanique variable, PhD thesis, Université de Marne la Vallée, France (2003)***.**

✓ Size of the specimens:

Cylindrical specimens – radius=1cm, height=16cm

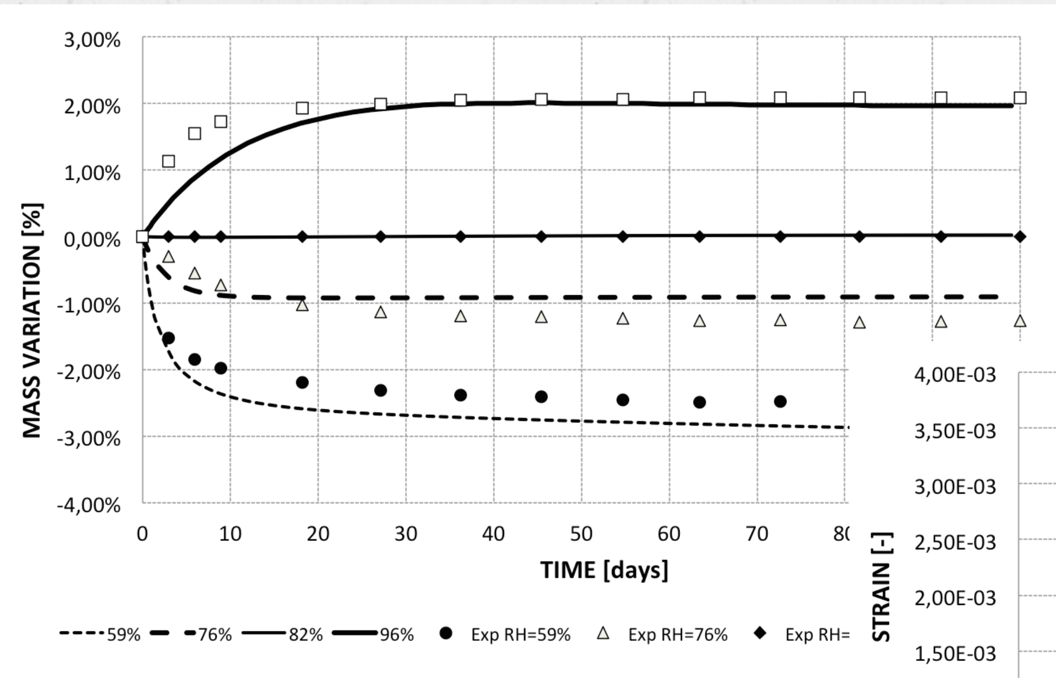
✓ Boundary conditions:

- convective heat and mass exchange:
  - RH_∞=82%, and then 59%, 76%, 82%, 96% or 100% kept constant in time with β_c=0.002 m/s (drying cases) and β_c=0.002 m/s (swelling cases)
  - T=60°C with α_c=5 W/Km^2
- surface mechanical load: unloaded

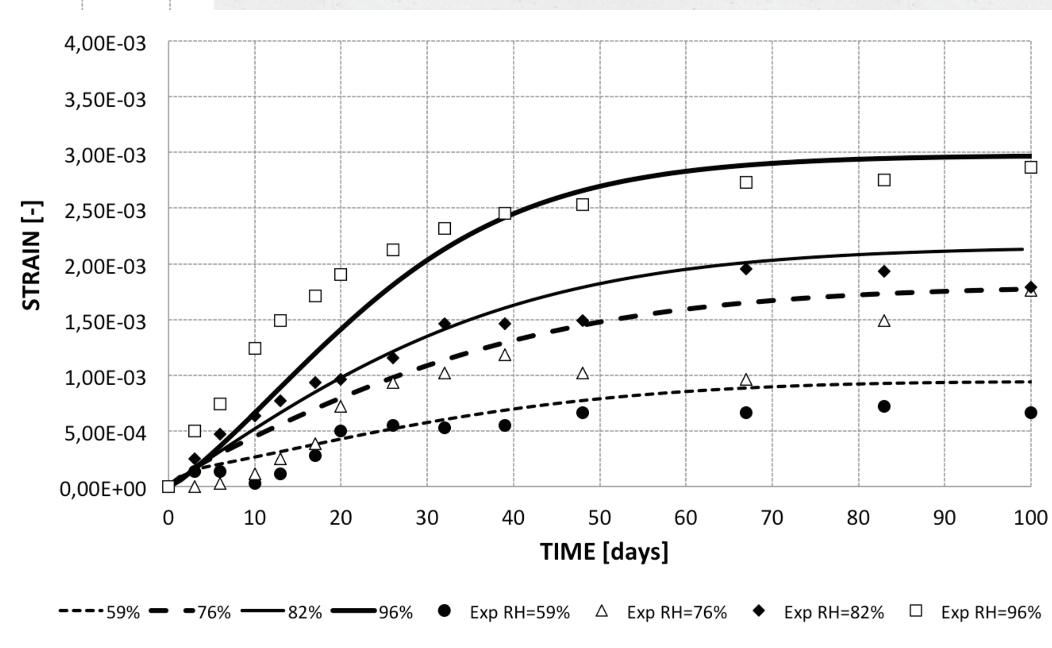
Experimental-numerical results comparison

Poyet's experimental tests at constant relative humidity

Mass variation



ASR strain evolution



Experimental-numerical results comparison

Poyet's experimental tests at variable relative humidity

✓ Material properties as in:

S. Poyet, Etude de la dégradation des ouvrages en béton atteints de la réaction alcali–silice: approche expérimentale et modélisation numérique multi-échelle des dégradations dans un environnement hydrochemo–mécanique variable, PhD thesis, Université de Marne la Vallée, France (2003).

✓ Size of the specimens:

Cylindrical specimens – radius=1cm, height=16cm

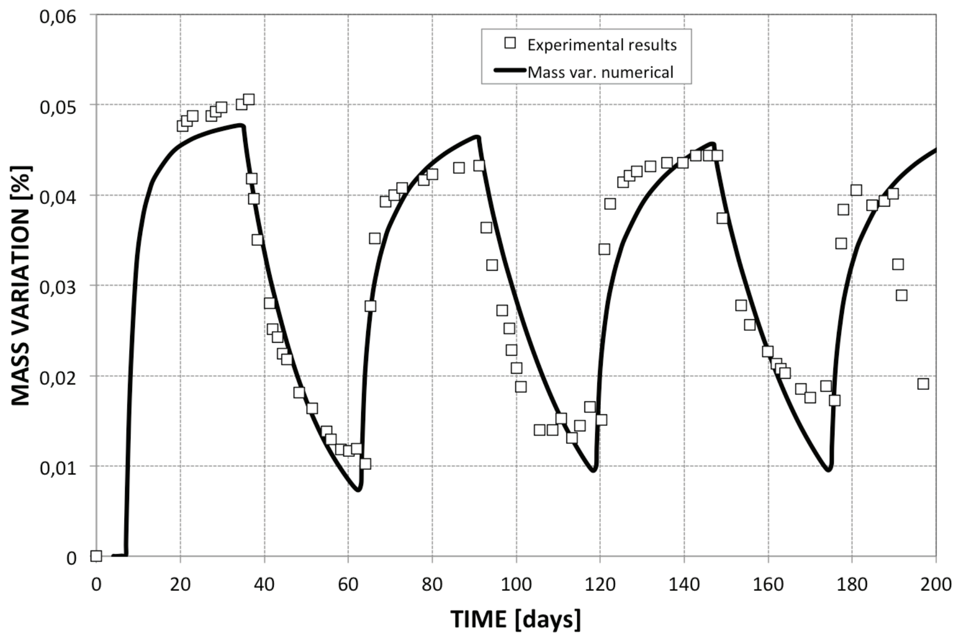
✓ Boundary conditions:

- convective heat and mass exchange:

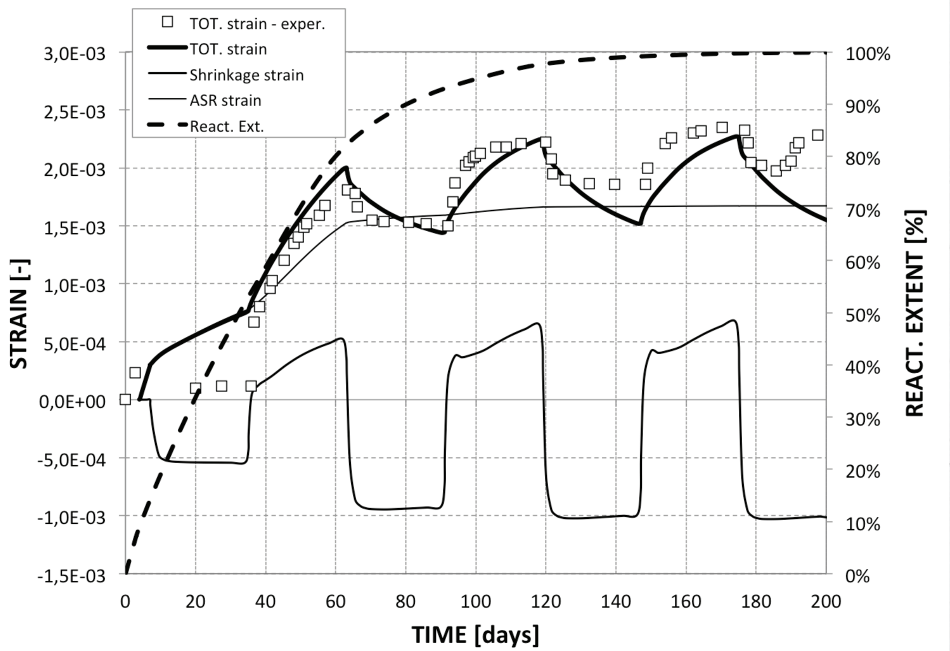
- RH_∞=59-96% variable in time with two different cycles: short (14 days) and long (28 days) β_c=0.002 m/s (drying phases) and β_c=0.002 m/s (swelling phases)
- T=60°C with α_c=5 W/Km^2

Experimental-numerical results comparison

Poyet's experimental tests at variable relative humidity (long cycle)



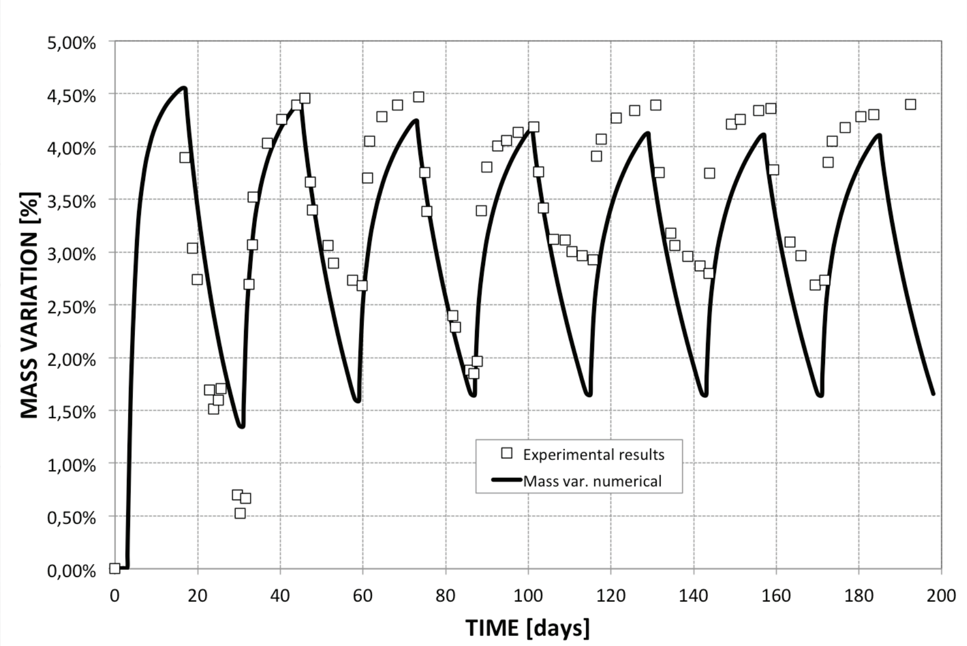
Mass variation



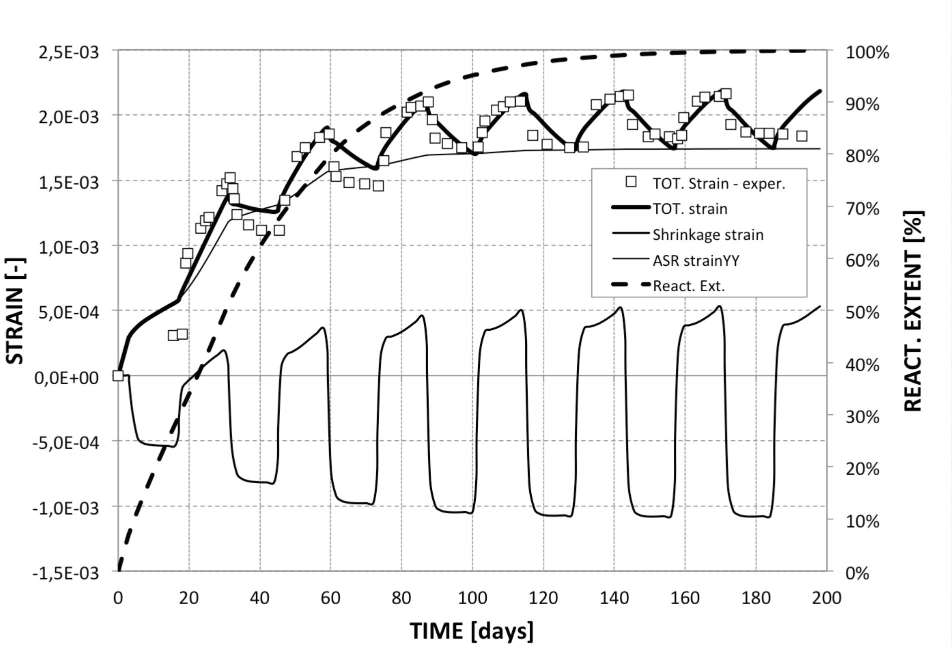
ASR strain and react. extent evolution

Experimental-numerical results comparison

Poyet's experimental tests at variable relative humidity (short cycle)



Mass variation



ASR strain and react. extent evolution

Kinetics of freezing process in porous materials

Non-Equilibrium approach: the present model

In this work freezing/melting process is modelled as a ***non-equilibrium process*** *(i.e. taking into account its kinetics):*

Evolution Law:

$$\dot{s}_i = A_{fr} \dot{\Gamma}_{fr}$$

From linear thermodynamics of chemical reactions, we can express the rate of freezing as:

$\dot{\Gamma}_{fr} = k\,A_{fr}$ *where the proportionality constant, k, is assumed in the following form (Coussy):*

$k = \dfrac{1}{RT\tau_{fr}}$ *Where τ_{fr} is the characteristic time of the process*

Kinetics of freezing process in porous materials

Non-Equilibrium approach: the present model

The actual level of liquid water in the pores is:

$$S_w = S_w\left(r_{pore}\right) = S_w\left(\frac{2\gamma_{w/gw}}{r_{pore}}\right) = S_w\left(p^c\right)$$

so, there is freezing when this saturation degree is greater than the corresponding value at equilibrium, i.e. ***capillary pressure during freezing is lower than the corresponding value at equilibrium****.*

Ice mass source - FREEZING

$$\text{if } p^c_{fr} < p^c_{fr,eq}\left(T\right) \text{ and } \dot{T} < 0: \quad \dot{m}_{fr/w} = -n\rho^w S_w \frac{v_w}{RT}\frac{p^c_{fr} - p^c_{fr,eq}}{\tau_{fr}};$$

$$\text{otherwise}: \quad \dot{m}_{fr/w} = 0.$$

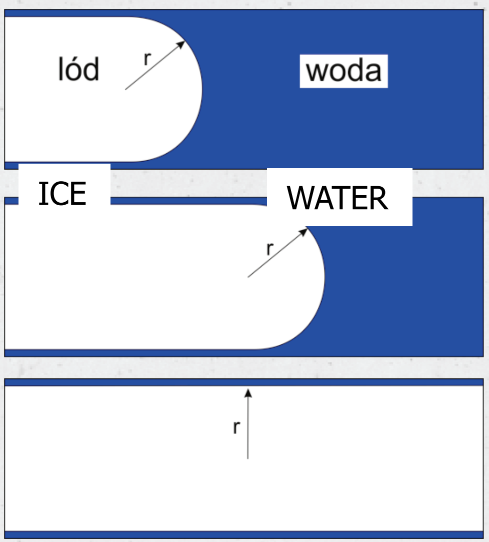
This relationship was obtained by assuming a ***spherical shape*** *of the liquid water / ice meniscus during freezing.*

Kinetics of freezing process in porous materials

Non-Equilibrium approach: the present model

Freezing-thawing hysteresis

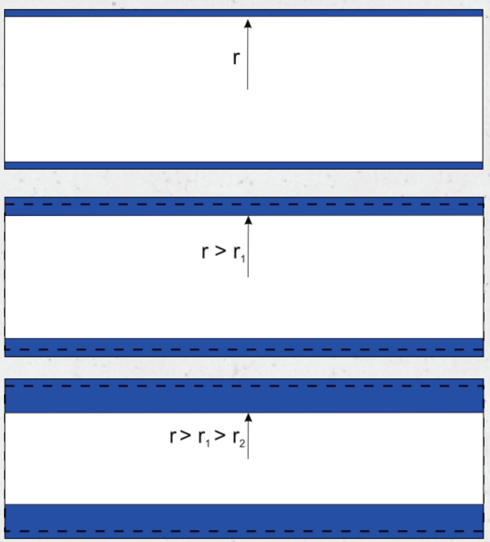
Freezing



curvature:

$$\kappa_{CL} = \frac{2}{r}, \quad r = r_p - \delta$$

Thawing



curvature:

$$\kappa_{CL} = \frac{1}{r}, \quad r = r_p - \delta$$

Ice-water equilibrium:

$$\Delta T \approx \frac{\gamma_{CL} \kappa_{CL}}{\Delta S_{fv}}$$

Kinetics of freezing process in porous materials

Non-Equilibrium approach: the present model

The temperature of freezing and melting is DIFFERENT *(due to the different shape of the "w/ice" interface during the processes)*

From experimental tests (i.e. DSC) or by supposing a shape for this interface (i.e. cylindrical for melting and spherical for freezing), we can define the ratio of the curvatures as:

$$\bar{\lambda}(S_w) = \frac{T_m^* - T_m(\kappa_{pore})}{T_m^* - T_{fr}(r_{pore})} \cong \frac{\gamma_{ice,w}\kappa_{ice,w}^{m}}{\gamma_{ice,w}\kappa_{ice,w}^{fr}} = \frac{\kappa_{ice,w}^{m}}{2/r_{pore}}$$

Ice mass source - MELTING

$$\text{if } p_{fr}^c > p_{m,eq}^c(T) \text{ and } \dot{T} > 0: \quad \dot{m}_{fr/w} = -n\rho^w S_w \bar{\lambda}(S_w)\frac{v_w}{RT}\frac{p_{fr}^c - p_{m,eq}^c}{\tau_m};$$

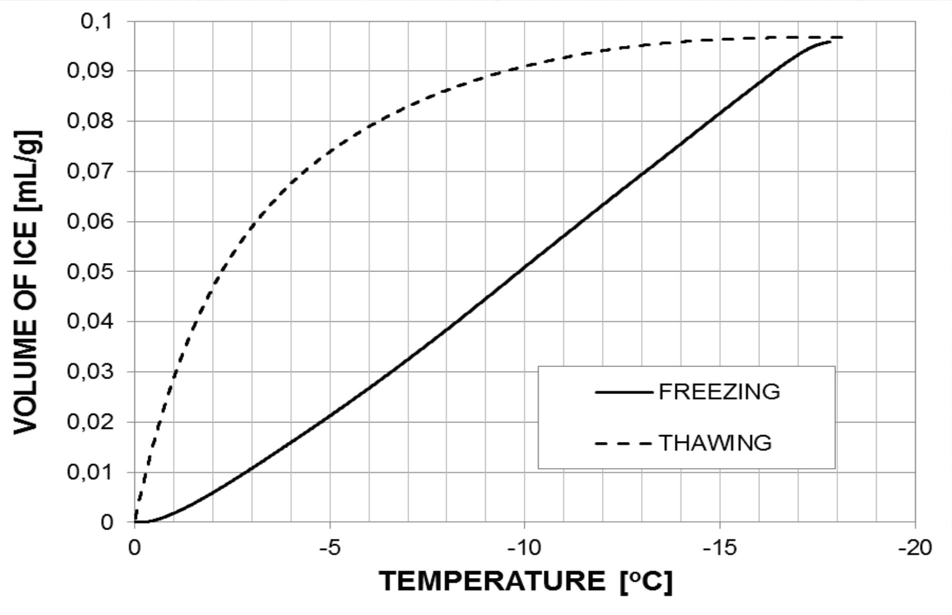
$$\text{otherwise}: \quad \dot{m}_{fr/w} = 0.$$

with $p_{m,eq}^c = p_{fr,eq}^c / \bar{\lambda}(S_w)$

Kinetics of freezing process in porous materials

First conclusion:

1. *This means that at a given temperature, water freezing starts at higher values of saturation degree than melting (i.e. the saturation degree corresponds to 2 times larger pore entrance radius).*
2. *Or, alternatively, freezing of water in pores of a given entrance radius starts at lower temperature than melting of ice in the same pores.*



Volume of ice in the pores of a fully water saturated cement mortar at different temperature, during freezing and melting, measured by means of Differential Scanning Calorimeter (DSC).

Modelling Freezing Process

First numerical validation of the model

- ✓ Data of the simulation correspond to the tests performed by **Scherer & Sun 2010**:
  - o DSC test (Differential Scanning Calorimeter) for measuring the ice formation;
  - o DMA test (Differential Mechanical Analyzer) for measuring dimensional changes;
  - o Material: mortar (STM Type I ordinary Portland cement) with two amounts of entrained air (0 and 6 vol.%).

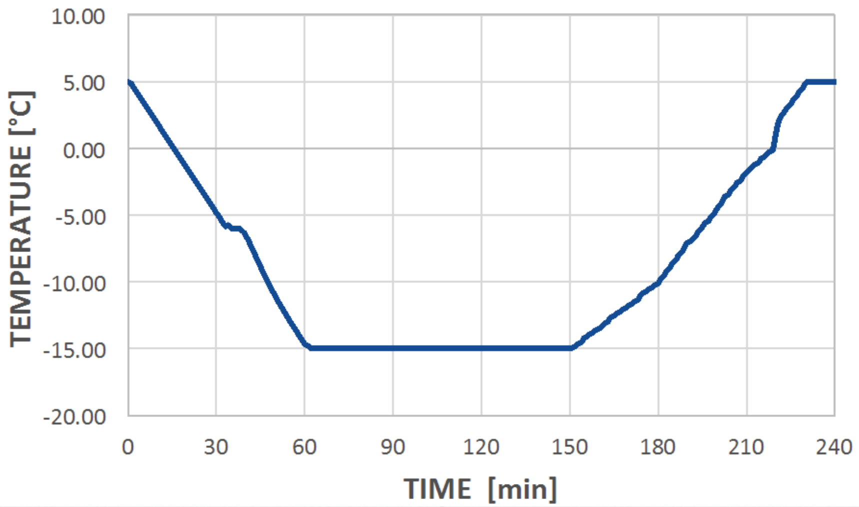
- ✓ Initial and Boundary conditions:

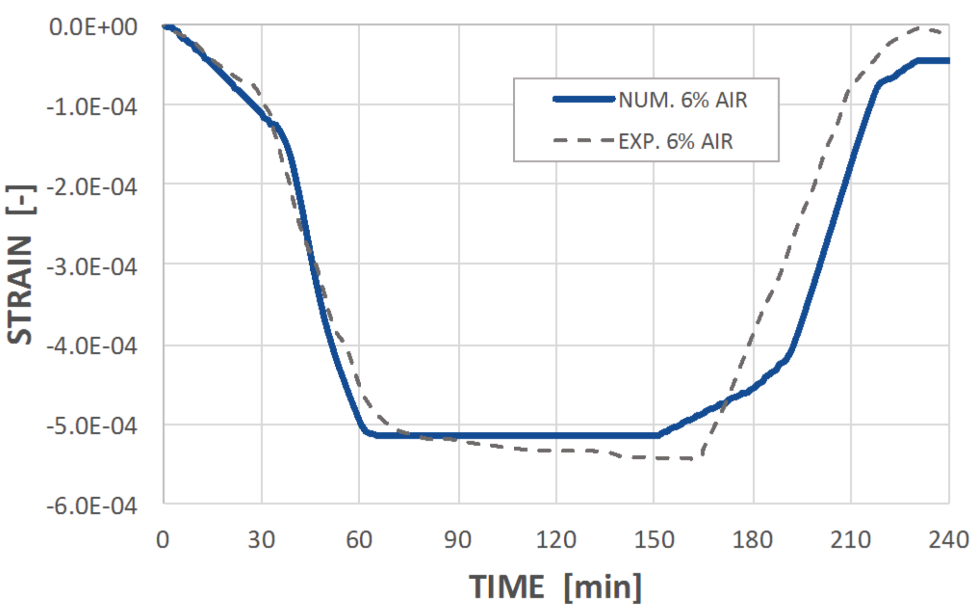
  - heat and mass exchange:
    - the specimen is completely sealed;
    - T_{∞} varying in time (see the graphs): two cycles with minimum temperature equal to -15°C and -40°C respectively;
    - α_c=30 W/Km^2

  - mechanically unloaded

Modelling Freezing Process

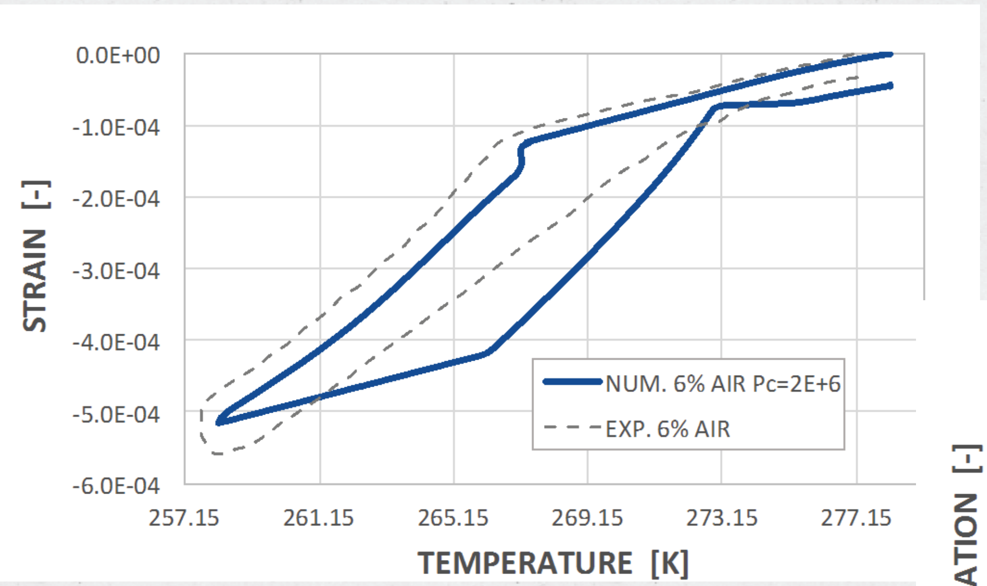
Cycle at -15°C – material with 6% of entrained AIR

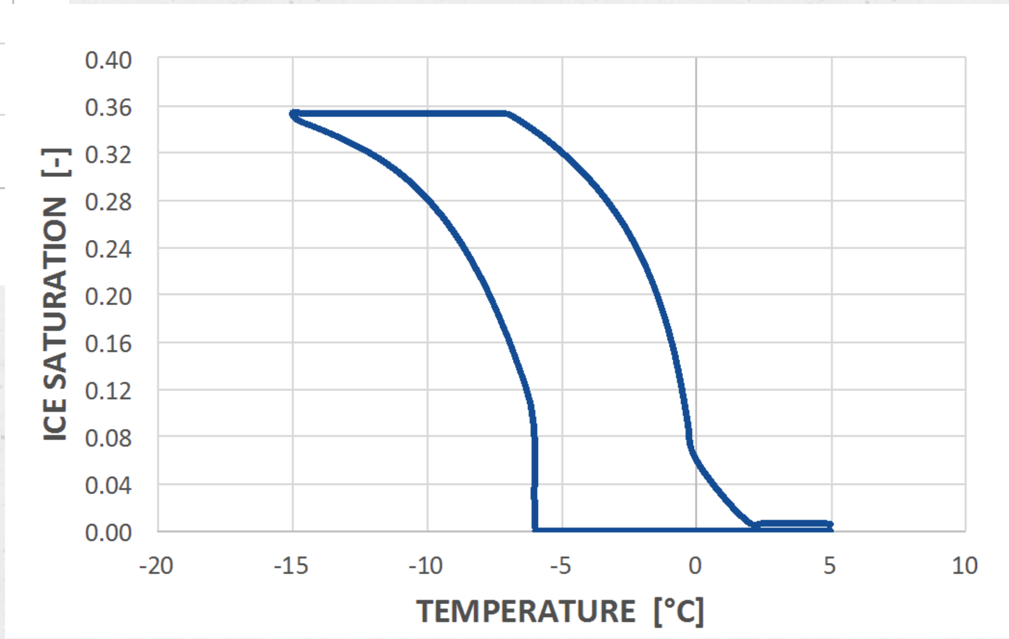




Modelling Freezing Process

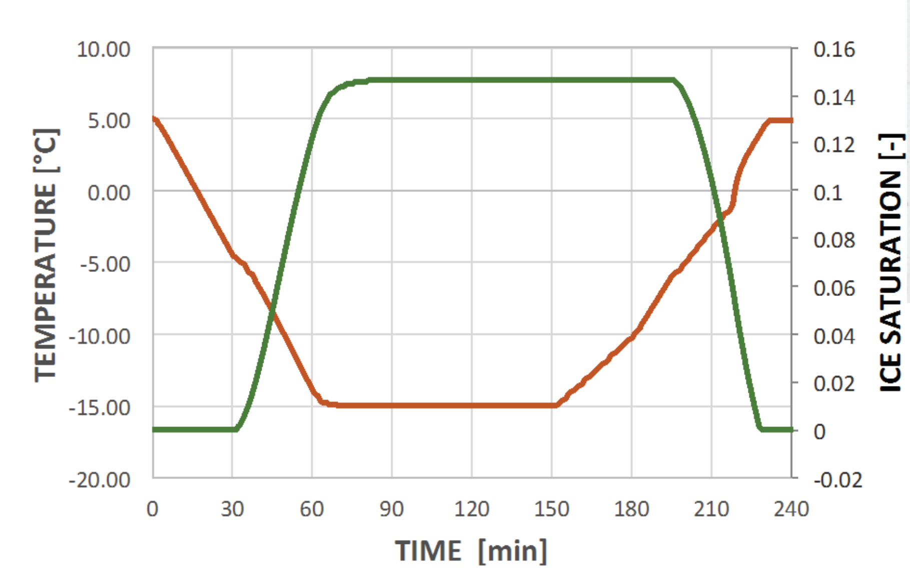
Cycle at -15°C – material with 6% of entrained AIR

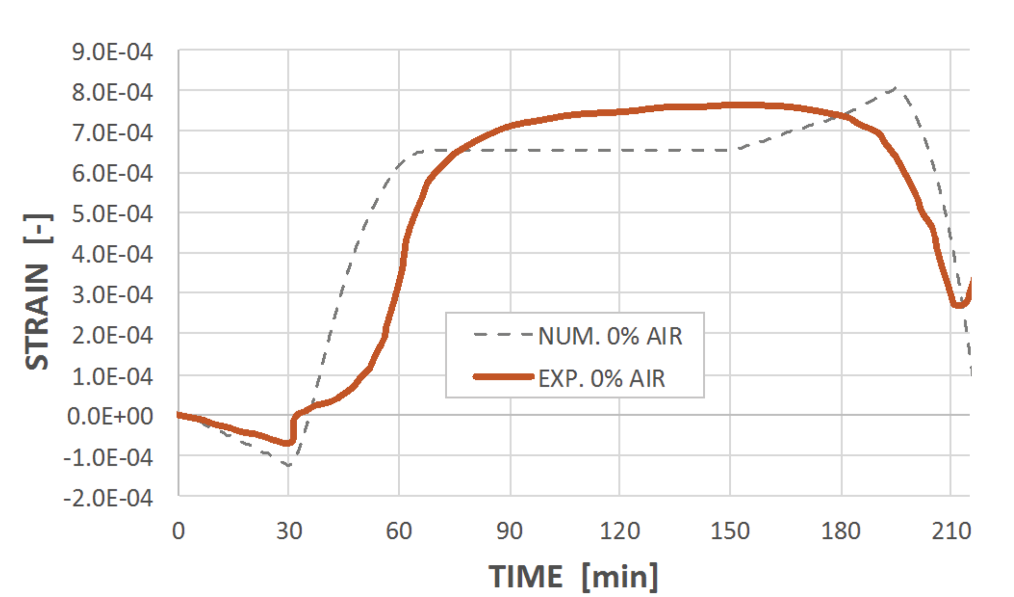




Modelling Freezing Process

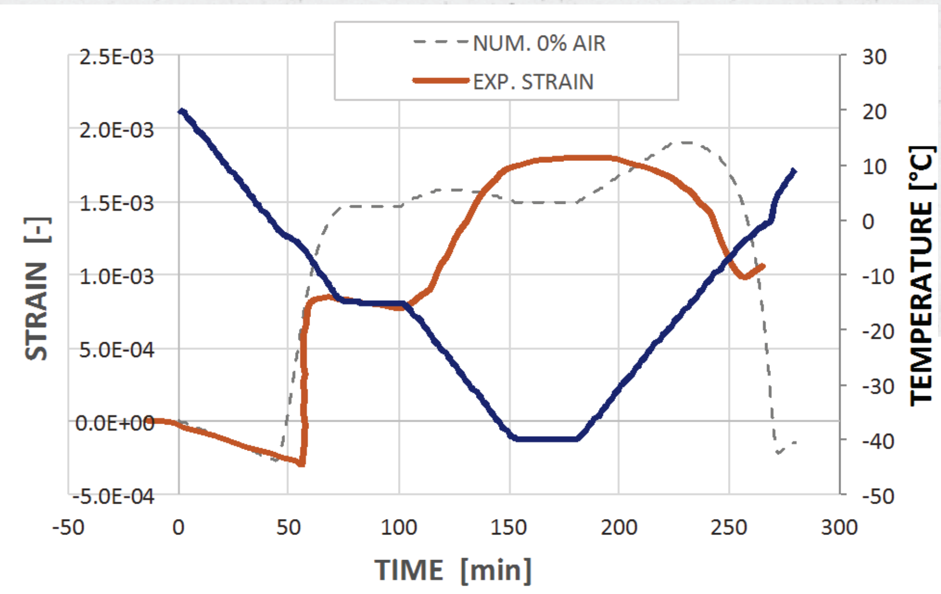
Cycle at -15°C – material with 0% of entrained AIR

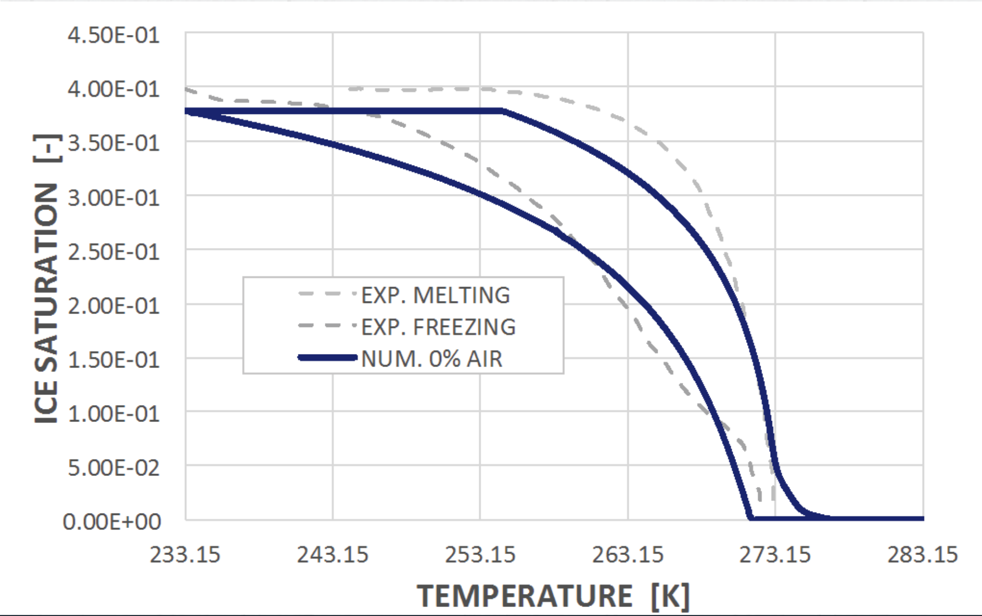




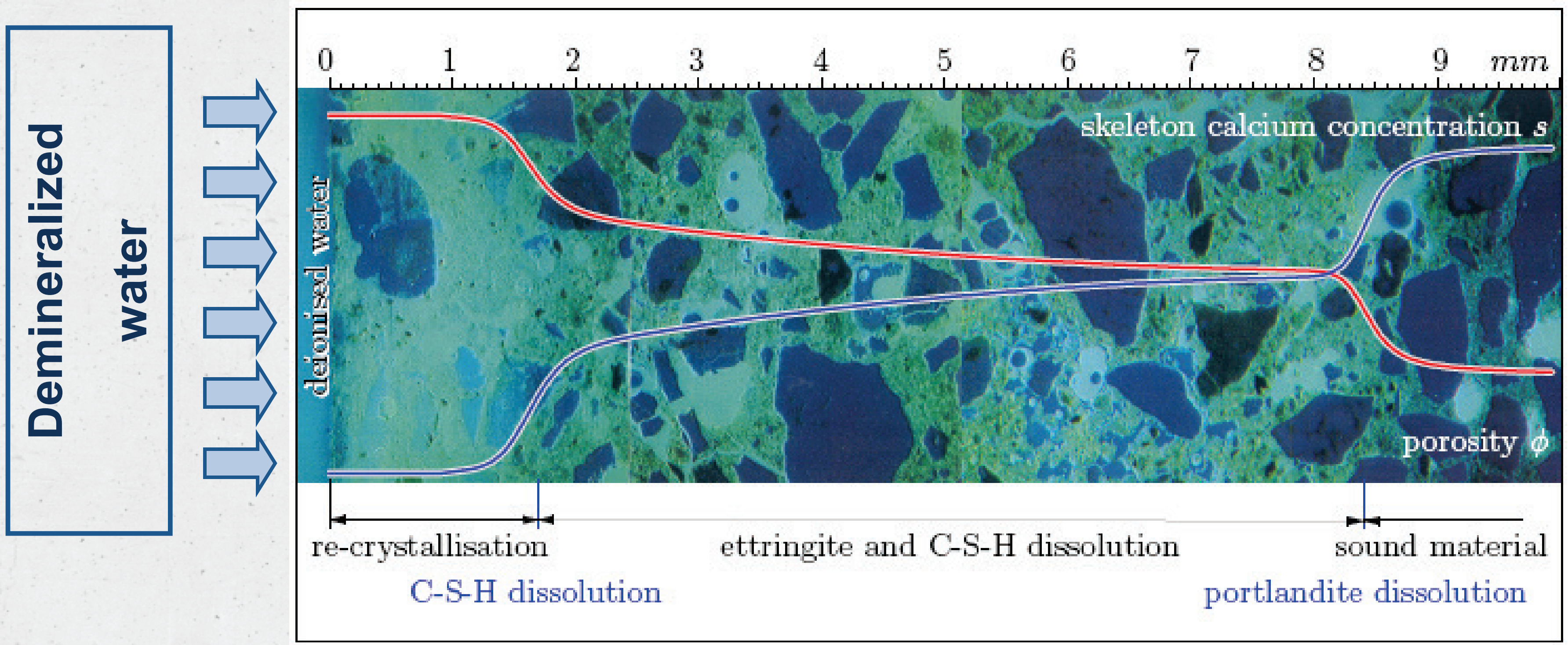
Modelling Freezing Process

Cycle at -40°C – material with 0% of entrained AIR





Modelling Concrete Leaching



Picture of a leached cement paste sample, obtained by means of microscopic analysis in a fluorescent light.

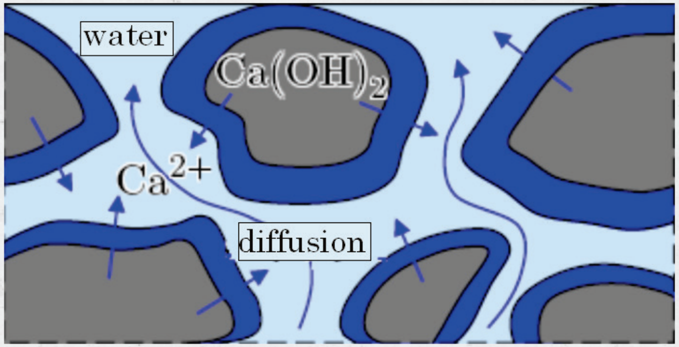
Equilibrium based models: Gérard (1996), Kuhl et al. (2004), Kuhl and Meschke (2007)

Process kinetics based models:
Ulm, Torrenti, Adenot – *J. Engineering. Mechanics,* 1999
Gawin, Pesavento, Schrefler - Part 1 & Part 2 , *Solids and Structures,* 2008
Gawin, Pesavento, Schrefler, CMAME 2009.

Concrete leaching process kinetics

Chemical reactions leading to calcium leaching process

- **Portlandite** dissolution (calcium hydroxide)



$$Ca(OH)_2 \Leftrightarrow Ca^{2+} + 2OH^-$$

- **ettringite** dissolution

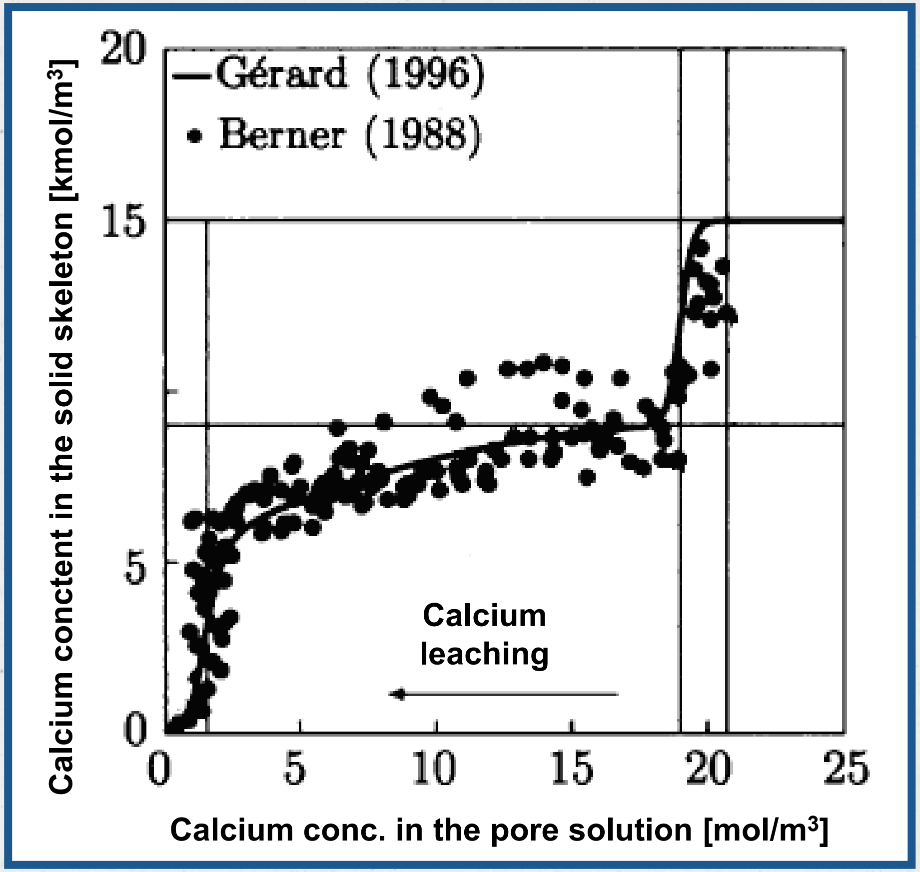
$$Ca_6Al_2O_6(SO_4)_3 \cdot 32H_2O \Leftrightarrow 6Ca^{2+} + 2Al(OH)_4^- + 3SO_4^{2-} + 4OH^- + 26H_2O$$

- dissolution of different phases of **CSH gel**

$$nCaO \cdot SiO_2 \cdot nH_2O \Leftrightarrow nCa^{2+} + H_3SiO_4^- + [2n-1]H_2O$$

Concrete leaching process kinetics

Curve describing equilibrium between solid and liquid calcium



Concrete leaching process kinetics

Thermodynamic description of the process

[Ulm, Torrenti, Adenot – J. Engng. Mech. 1999]

$$A_s = \mu^s - \Gamma = \eta \frac{ds_{Ca}}{dt}$$

η- parameter dependent on micro-diffusion of Ca^{2+},

μ^s – chemical potential of liquid calcium,

Γ– chemical potential of solid calcium.

$$dA_s = RT\frac{dc_{Ca}}{c_{Ca}} - \mathbf{B} : \left(d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}^p\right) + kd\chi - \kappa\, ds_{Ca}$$

Effect of *Ca* concentration

Effect of the material elastic properties

Effect of micro-cracking

Effect of *Ca* content in skeleton

Concrete leaching process kinetics

Thermodynamic description of the process

[Ulm, Torrenti, Adenot – J. Engng. Mech. 1999]

$$A_s = \mu^s - \Gamma = \eta \frac{ds_{Ca}}{dt}$$

η- parameter dependent on micro-diffusion of *Ca*$^{2+}$,

/s – chemical potential of liquid calcium,

℘– chemical potential of solid calcium.

$$dA_s = RT\frac{dc_{Ca}}{c_{Ca}} - \mathbf{B}:\left(d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}^p\right) + kd\chi - \kappa\, ds_{Ca}$$

Effect of *Ca* concentration

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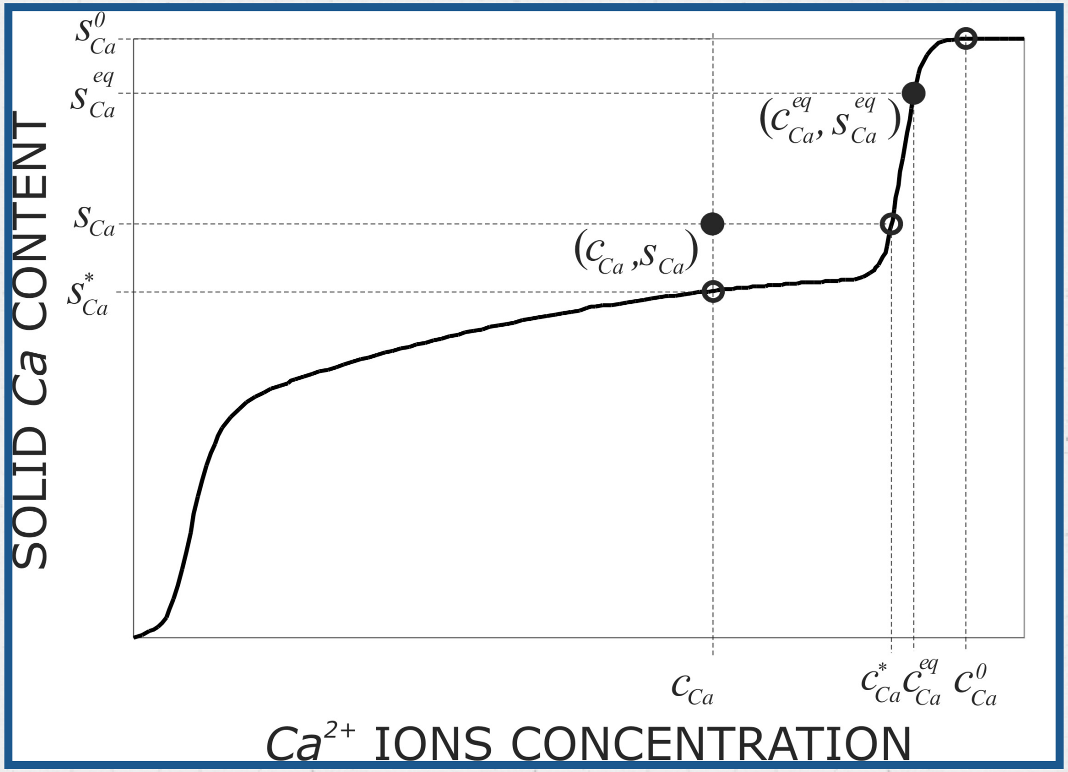
Concrete leaching process kinetics

Thermodynamic description of the process



$$\frac{\partial s_{Ca}}{\partial t} = \frac{1}{\eta}\left[\int_{s^0_{Ca}}^{s^*_{Ca}} \kappa\left(\bar{s}, T\right) d\bar{s} - \int_{s^0_{Ca}}^{s_{Ca}} \kappa\left(\bar{s}, T\right) d\bar{s}\right]$$

R – universal constant of gas,

/ – process equilibrium constant,

/ - parameter dependent on micro-diffusion of Ca^{2+}

$$\tau_s = \frac{\eta}{RT}$$

Characteristic time of the process

Concrete leaching process kinetics

Extension to the non-isothermal conditions

The values of the *equilibrium constant*

$$\kappa\left(s_{Ca},T\right)$$

can be found from the thermodynamic equilibrium condition at temperature *T*, which can be written in the incremental form as

$$dA_s = RT\frac{dc_{Ca}}{c_{Ca}} - \kappa\, ds_{Ca} = 0$$

in this way we get

$$\kappa\left(s_{Ca},T\right) = \frac{RT}{c_{Ca}}\left(\left.\frac{ds_{Ca}}{dc_{Ca}}\right|_T\right)^{-1}$$

and taking into account the expression

$$c_{Ca}^{ef}\left(T\right) = c_{Ca} \times \exp\left[-\frac{E_{leach}}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$$

one can write

$$\kappa\left(s_{Ca},T\right) = \kappa\left(s_{Ca},T_{ref}\right)\frac{T}{T_{ref}}$$

This allows writing the general relationship describing the thermodynamic of the process as:

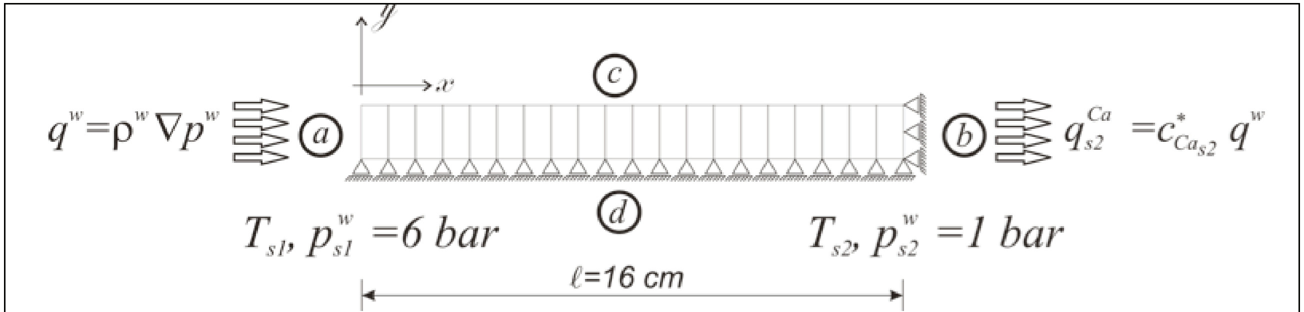
$$\frac{\partial s_{Ca}}{\partial t} = \frac{1}{\tau_{leach}\left(T\right)}\frac{1}{RT_{ref}}\left[\int_{s_{Ca}^0}^{s_{Ca}^*}\kappa\left(\bar{s},T_{ref}\right)d\bar{s} - \int_{s_{Ca}^0}^{s_{Ca}}\kappa\left(\bar{s},T_{ref}\right)d\bar{s}\right]$$

i.e. the dependence on the temperature is concentrated in the function $\tau_{leach}\left(T\right)$

Numerical simulation results

Modeling of a wall subject to reaction-diffusion-advection process

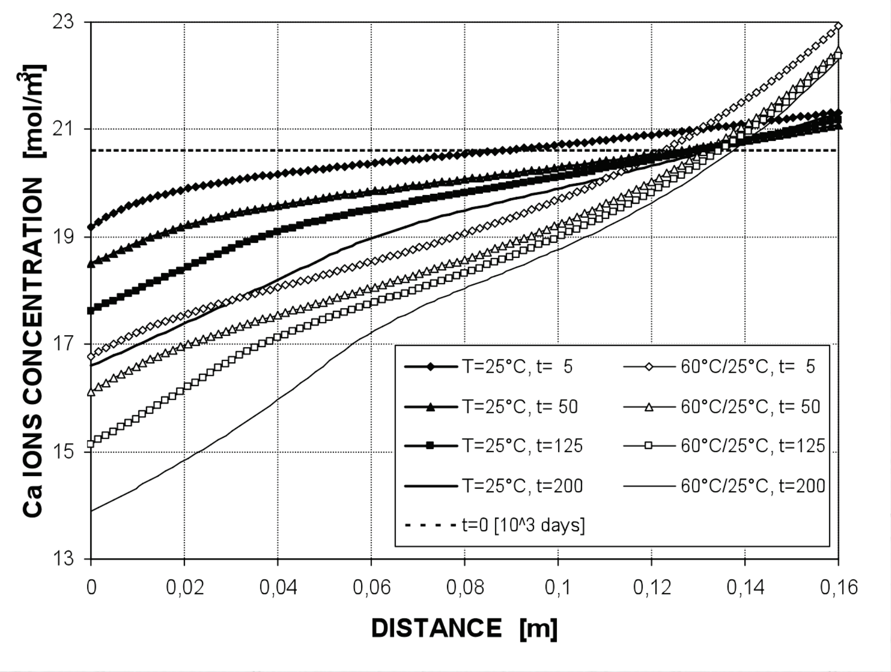
Boundary Conditions

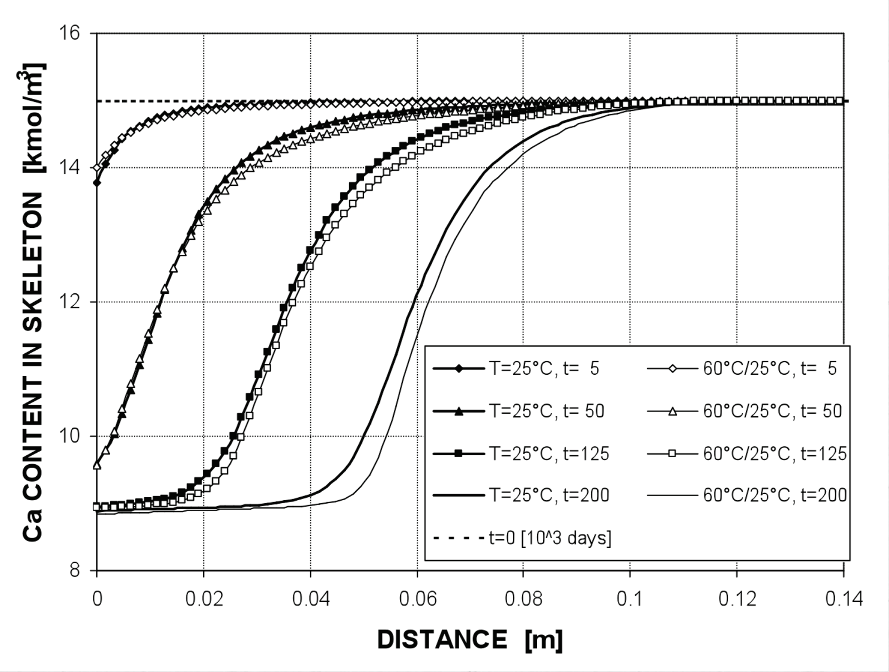


BC type	Case	T_0	BC on side *a*		BC on side *b*	
			water	*temperature*	*water*	*temperature*
"Natural"	*1*	60°C	p^w_{s1} =6 bar	T_{s1}=60°C	p^w_{s2} =1 bar	T_{s2}=60°C
	2	25°C	p^w_{s1} =6 bar	T_{s1}=25°C	p^w_{s2} =1 bar	T_{s2}=25°C
	3	25°C	p^w_{s1} =6 bar	T_{s1}=60°C	p^w_{s2} =1 bar	T_{s2}=25°C
	4	60°C	p^w_{s1} =6 bar	T_{s1}=25°C	p^w_{s2} =1 bar	T_{s2}=60°C

Numerical simulation results

Reaction-diffusion-advection process: 25°C and 60°C-25°C cases



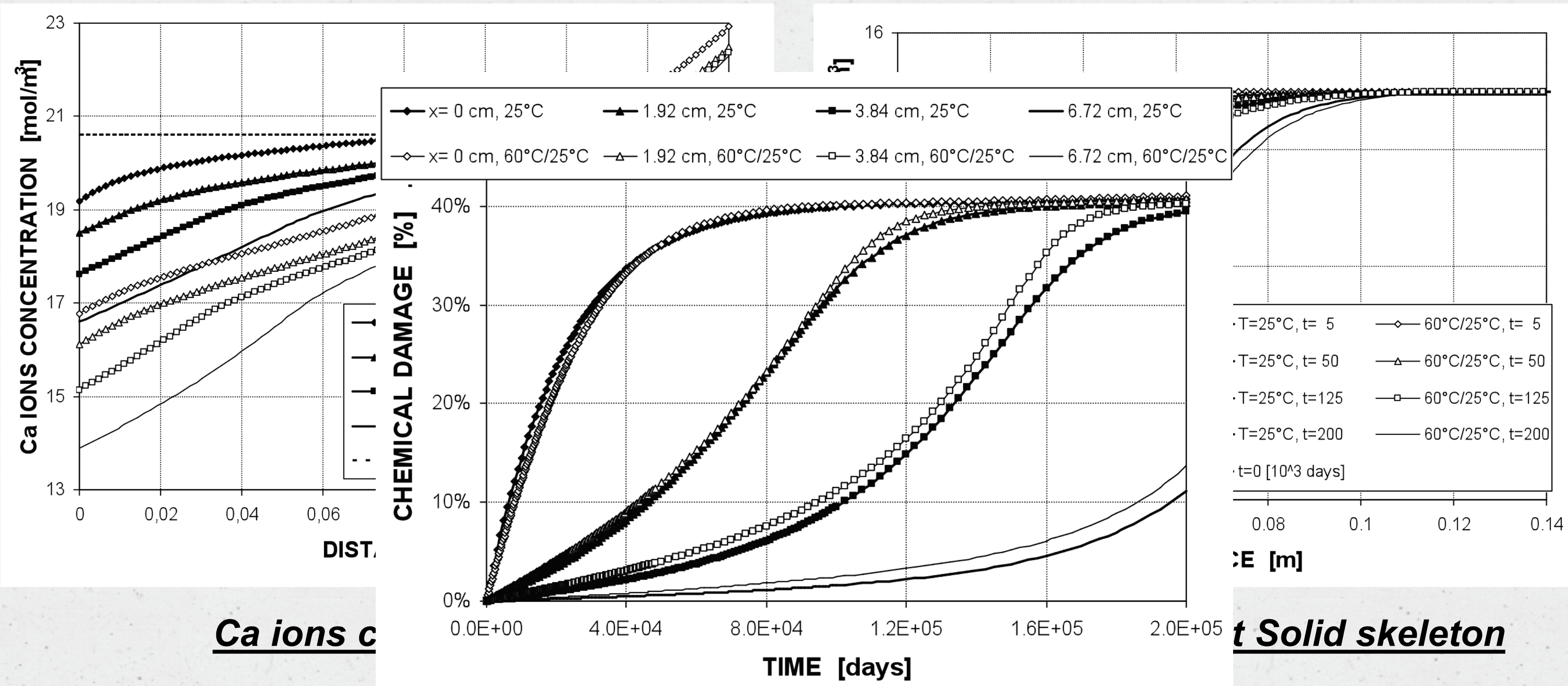


Ca ions concentration

Calcium content Solid skeleton

Numerical simulation results

Reaction-diffusion-advection process: 25°C and 60°C-25°C cases

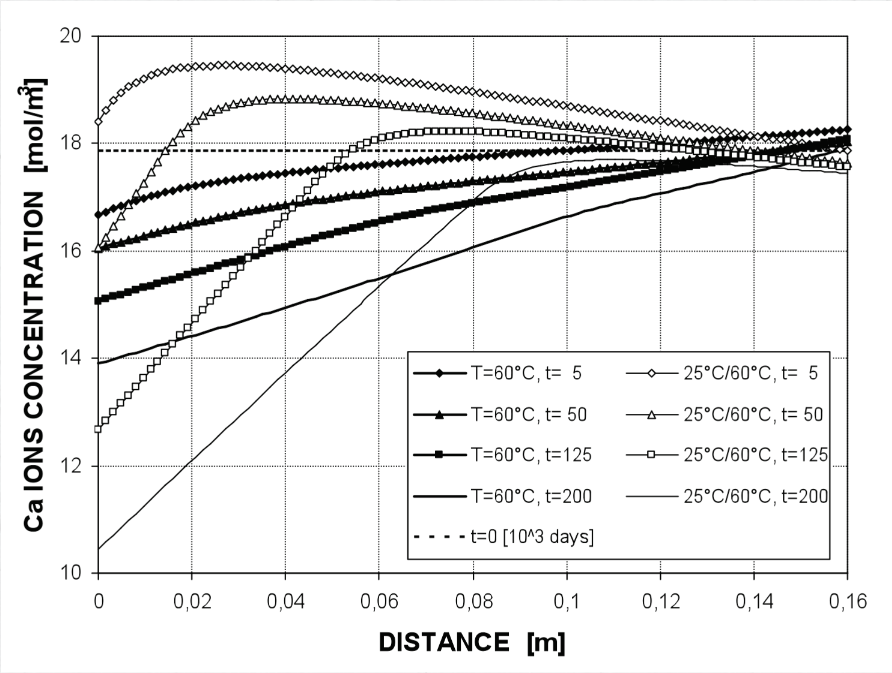


Ca ions c ***t Solid skeleton***

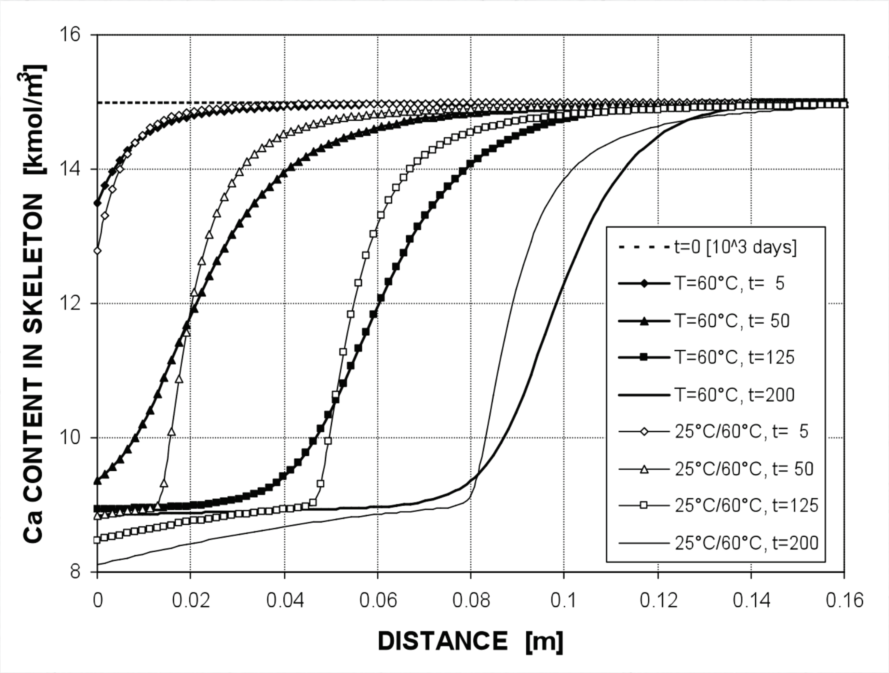
Chemical Damage

Numerical simulation results

Reaction-diffusion-advection process: 60°C and 25°C-60°C cases



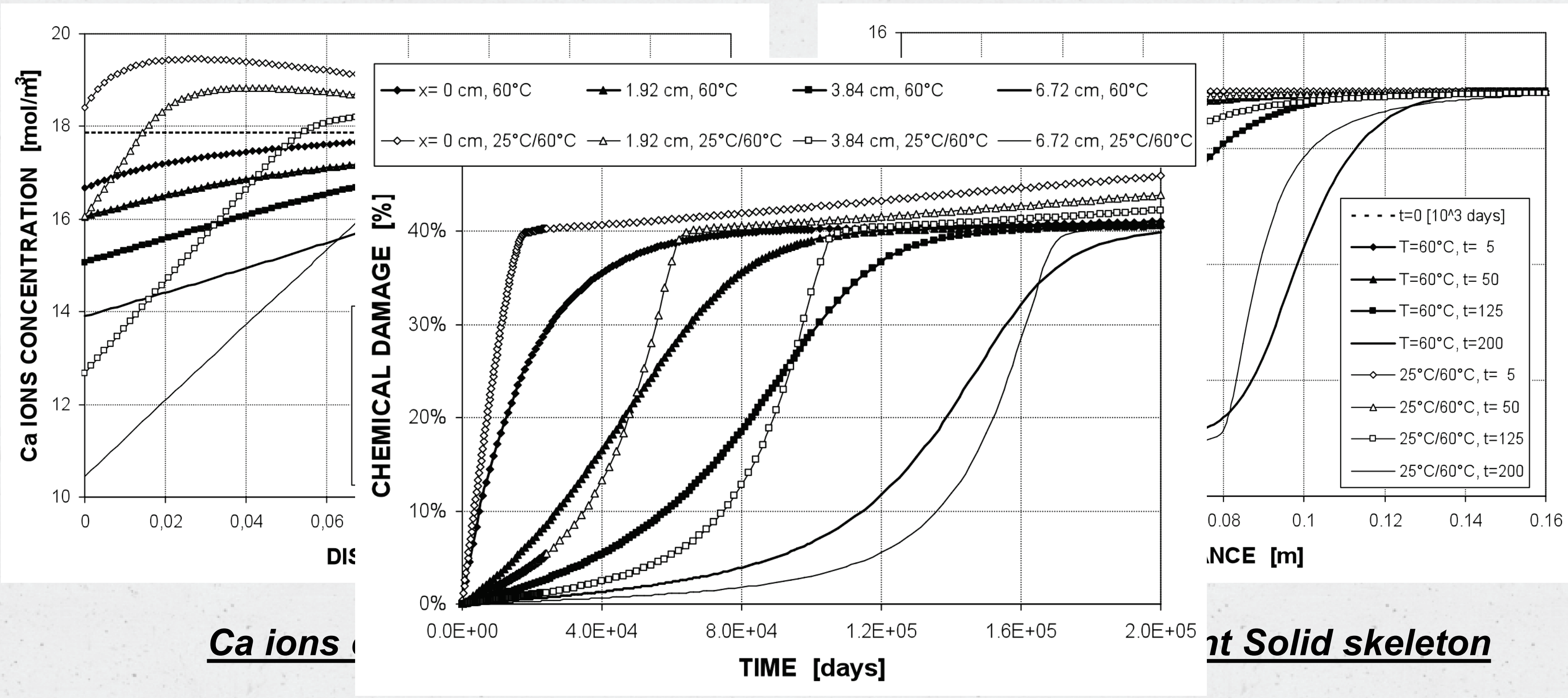
Ca ions concentration



Calcium content Solid skeleton

Numerical simulation results

Reaction-diffusion-advection process: 60°C and 25°C-60°C cases

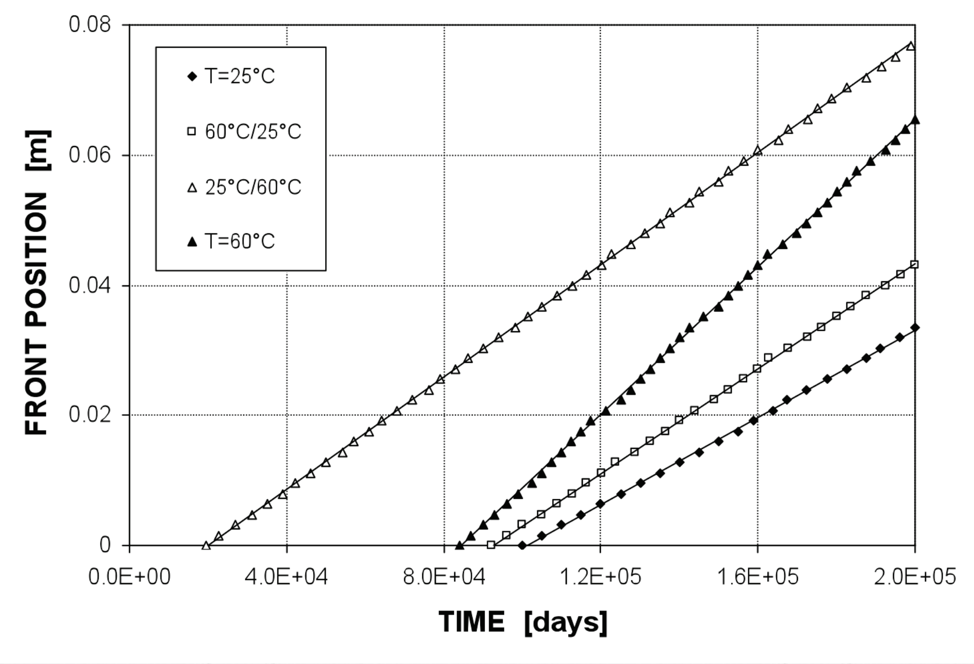


Ca ions ... ***nt Solid skeleton***

Chemical Damage

Numerical simulation results

Modeling of a wall subject to reaction-diffusion-advection process



Leaching front evolution

CONCLUSIONS

- A multiscale model based on the mechanics of multiphase porous media for the analysis of thermo-hygral-chemical and mechanical behaviour of concrete has been presented (this morning…).

- Three relevant applications of this model have been shown:
  - **Alkali-Silica Reaction** evolution and the strain development;
  - **Freezing/Melting** processes of cementitious materials;
  - Concrete exposed to chemical degradation by pure water (i.e. **leaching**) in both **isothermal** and **non-isothermal conditions**;

CONCLUSIONS

- ***Alkali-Silica Reaction model***:
  - The model accounts for both water content (i.e. **saturation**) and **temperature** influence on the reaction evolution and the strain development.
  - **Sorption isotherm** modifications due to the changes of the material microstructure are taken into account.
- ***Freezing-Melting process model***:
  - Phase changes are properly treated on the base of **Phase Change Thermodynamics** considering mechanical and chemical stability conditions.
  - The model considers the **kinetics of the freezing/melting processes**, taking also into account their different evolutions (i.e. the different shape of the ice/water interface during melting and freezing).
- ***Leaching model:***
  - The **leaching model** considers not only the diffusive calcium transport, as other existing models, but additionally also the **advective calcium flow**.
  - Calcium leaching process is modeled by considering **thermodynamic imbalance** of the calcium in solid and liquid phases, what allows for the description of **process kinetics**.

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Modeling of multi-species diffusion and effect of electrical double layer

Ouali Amiri - University of Nantes, France

Outline

- **Introduction: problem related to ionic transport**

- **Physicochemical phenomena linked to ionic ingress**

- **Modelling of chloride ingress in saturated porous media**

  Macroscopic approach: law Fick

  Multispecies approach: Electrical Double Layer (EDL) effect

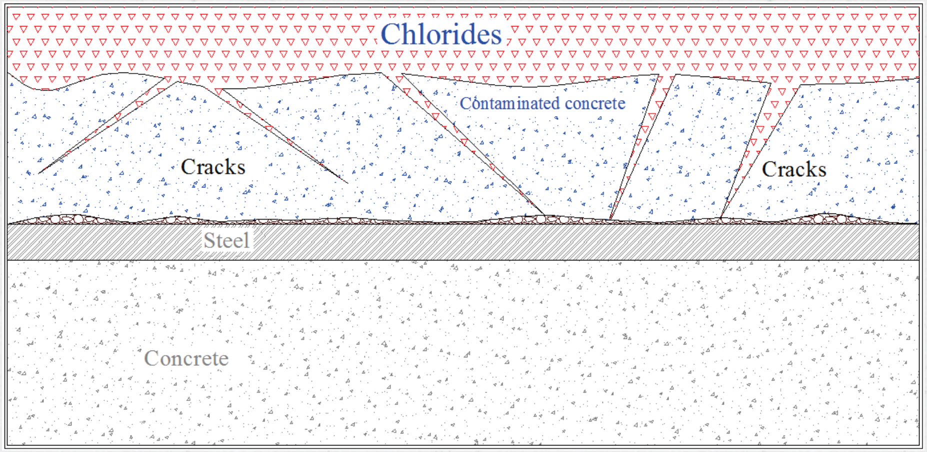
- **Conclusion**

1. Introduction : problem related to ionic transport

Steel in concrete are triply protected by:

- Concrete cover
- basic medium (pH ≈ 13)
- Existence of passif layer along the steel

What is then the problem??



Chloride, le CO_2...

1. Introduction : problem related to ionic transport

Severe degradation occurred on pier of Ré Bridge (south west in France) built in 1986

Economic issues :

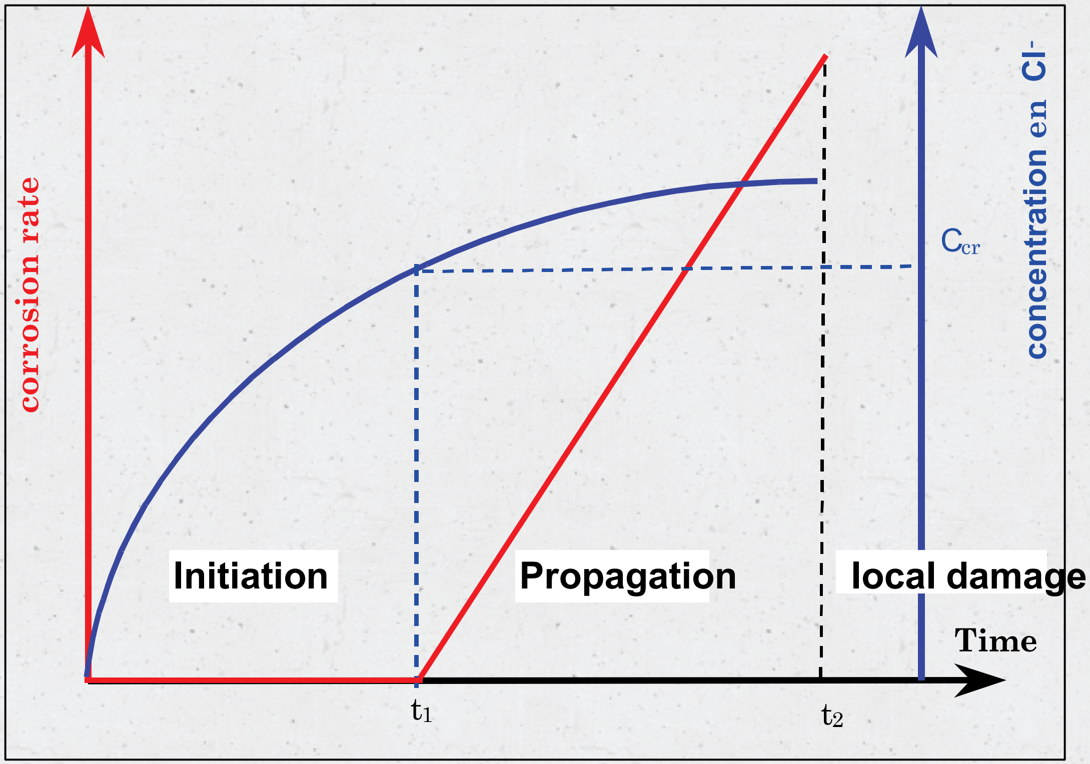
4% of GDP used for Restauration of reinforced concretes in OECD countries

OECD: The Organisation for Economic Co-operation and Development

GDP: Gross Domestic Product

1. Introduction : problem related to ionic transport

TUUTTI Diagram



Initiation Period : Chloride Profile , **diffusion coefficient**: durability parameter
Permeability, porosity, wetting-drying cycles…

Question often asked: which approach use?

2. Physico-chemical phenomena related to ionic transport

Which phenomena are occurring during diffusion?

- **Chemical interaction between chloride and cement matrix:**
  binding, crystallization…

- **Physical interaction between chloride and cement matrix:**
  Electrical double layer: Van Der waals Interactions

- **Electrostatic interactions between the ions of the pore solution:**
  potential electrostatic

- **Chemical activity of the pore solution: active concentration:**
  decreasing of initial concentration

3. Modelling of ionic transport in saturated porous media

Macroscopic Approach type Fick : Mono-specie

Transport equation

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - KC$$

Analytical Solutions : Linear isotherm

2 types of boundary conditions can be considered:

- **Semi-infinite Diffusion**: *bridge pier*: unsteady state: CTH method
- **Finite Diffusion**: *wall thin*: unsteady and steady state

Problem: The phenomena presented above are not taken into account
Another approach is then required

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

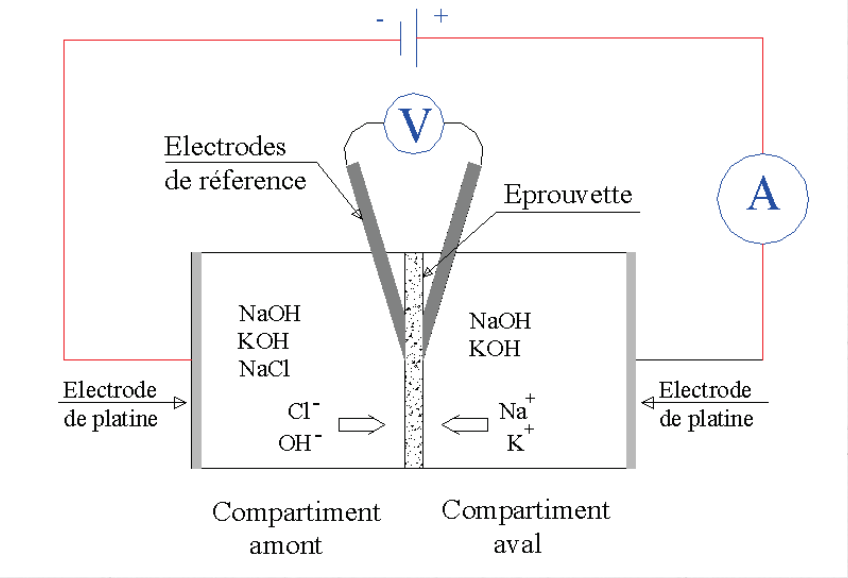
Flux equations (Nernst-Planck) conservation, electroneutrality, current density

$$\vec{j}_k = -QD_k \overrightarrow{\text{grad}} c_k + z_k \frac{F}{RT} c_k Q D_k \vec{E}$$

$$\text{div}\, \vec{j}_k + \varepsilon_L \frac{\partial c_k}{\partial t} = -\varepsilon_L \frac{\partial c_{bk}}{\partial t}$$

$$\sum_k z_k c_k = 0$$

$$\vec{i} = F \sum_k z_k \vec{j}_k$$



Additional interest:

Analysis of ionic transfer in electrical current terms

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

First result: Steady state study

- We can show in steady state

$$D_{eCl} = \frac{j_{Cl} RT}{c_{Cl,S} FE}$$

Mono-specie method overestimate the chloride concentration in the sample

- Comparison with mono-specie method

$$D_{eCl,\ up} = \frac{j_{Cl} RT}{c_{Cl,up} FE}$$

- Observation :

$$c_{Cl,S} \neq c_{Cl,up}$$

$$c_{Cl,S} = \frac{c_{Cl,up}}{c_{Cl,up} + c_{OH}} c_{OH}$$

Multi species, electroneutrality

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

Second result : Steady state study

Calculation of diffusion coeffcient by using current measurement:

Advtange of multi-species approach: Chloride dosage avoid: only current measurement is required

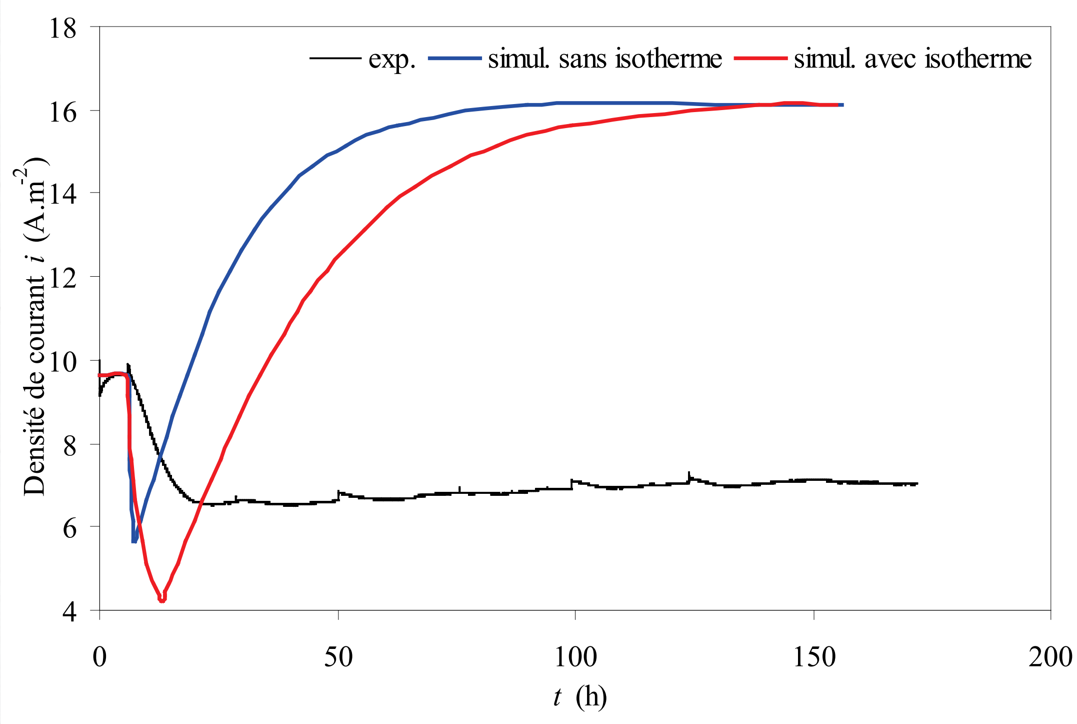
$$D_{eCl} = \frac{\left(i_i - i_f\right)RT}{c_{Cl,S}EF^2\left(\frac{D_{OH}}{D_{Cl}} - 1\right)}$$

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

Unsteady state study

Current density versus time into cement mortar w/c = 0,5



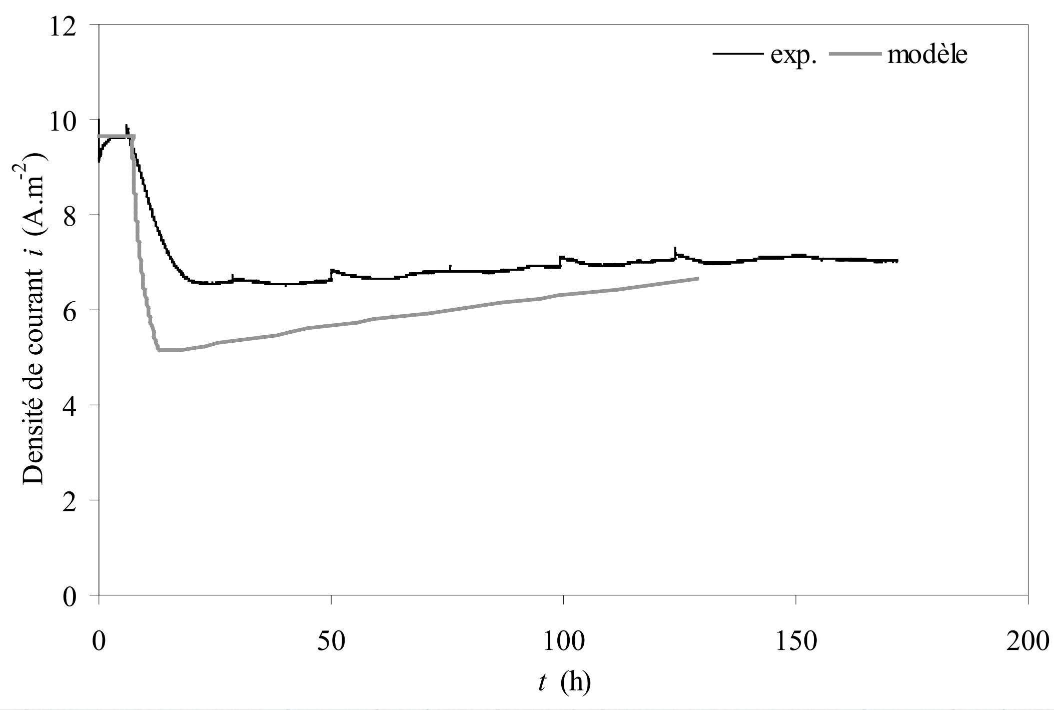
Observation : The simulated current is changing faster than the current measured

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

Unsteady state case

First Approach :Consideration of slowing down effect through corrected factor $C = 1/r_D$) affected to flux of cations (TRUC, 2000)

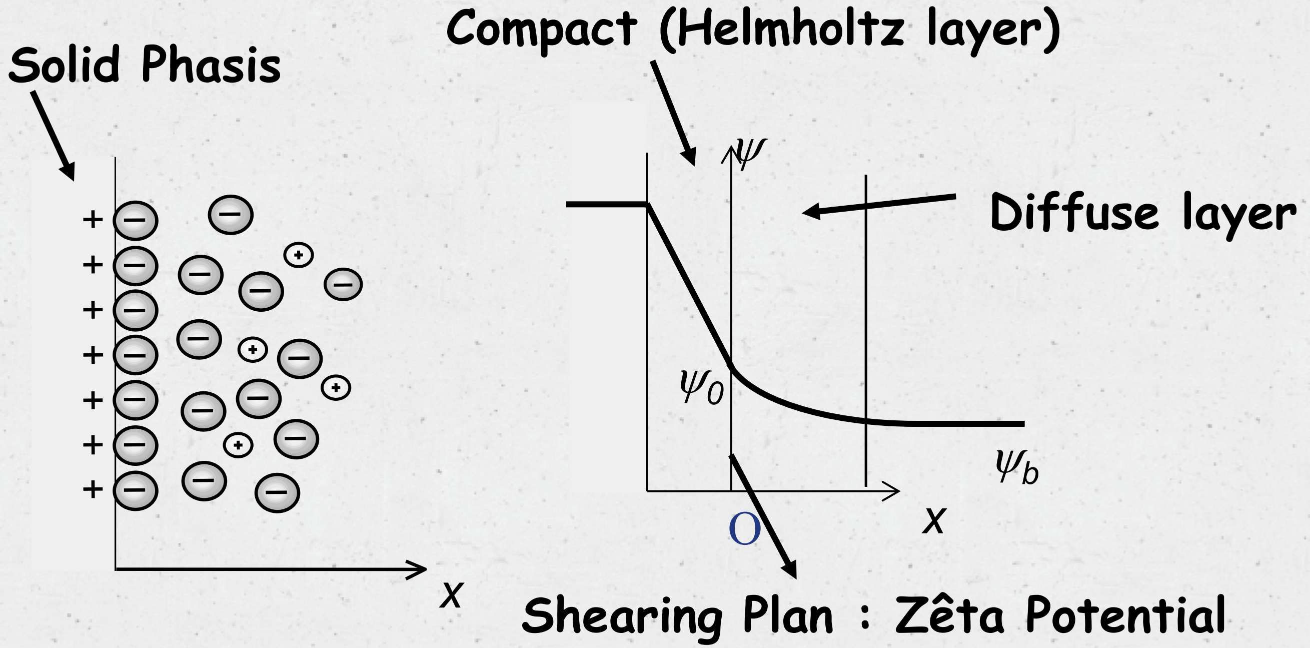


Result: Decreasing of simulated current when the flux cation is corrected

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

Second approach : Consideration of EDF through Stern Model



Hypothesis at microscopic Scale :

Geometry considered: capillary pore (Dubois 1992) : clay's medium

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

EDL effect: Main equations

Démarche

- Poisson Boltzmann 's equation

$$\frac{\partial^2 \delta\psi_+}{\partial X^2} = \frac{2F^2 c_{PC}}{RT\varepsilon} \sinh \delta\psi_+$$

$$\delta\psi_+ = -2Z \ln\left(\operatorname{cotanh} \frac{X_+ + \xi_0}{2} \right)$$

- Debye 'constant

$$\kappa = \sqrt{\frac{2F^2 c_{PC}}{RT\varepsilon}}$$

$$X_+ = \kappa X$$

Zêta pontential

$$\delta\psi_{+Ap} = -2Z \ln\left(\operatorname{cotanh} \frac{\xi_0}{2} \right)$$

Concentration of ions

Ionic Concentration in the bulk (outside diffuse layer)

$$c_k = c_{PC} \exp\left(-z_k \delta\psi_+ \right)$$

Assumption : semi-finite media

3. Modelling of ionic transport in saturated porous media

Electrical double layer Effect: Evolution of concentrations (in a pore)

Approximation de Padé (1853-1963) : weak and strong overlapping (Dufrêche *et al* (2001))

Cations

$$\frac{c_{k_+}}{c_{PC}} = \frac{\frac{1}{8\pi^2}\left(1+\frac{3}{\frac{qFd}{4ZRT\varepsilon}}\right)d_+^2}{1+\frac{1}{8\pi^2}\left(1+\frac{3}{\frac{qFd}{4ZRT\varepsilon}}\right)4\left(\tanh\frac{\xi_0}{2}-1\right)d_+ + \frac{1}{8\pi^2}\left(1+\frac{3}{\frac{qFd}{4ZRT\varepsilon}}\right)d_+^2} = K_+$$

Pore diameter

Zeta Potential

Anions

$$K_- = K_+ - \frac{2q}{F\ {}_{P}c\ C}$$

Result

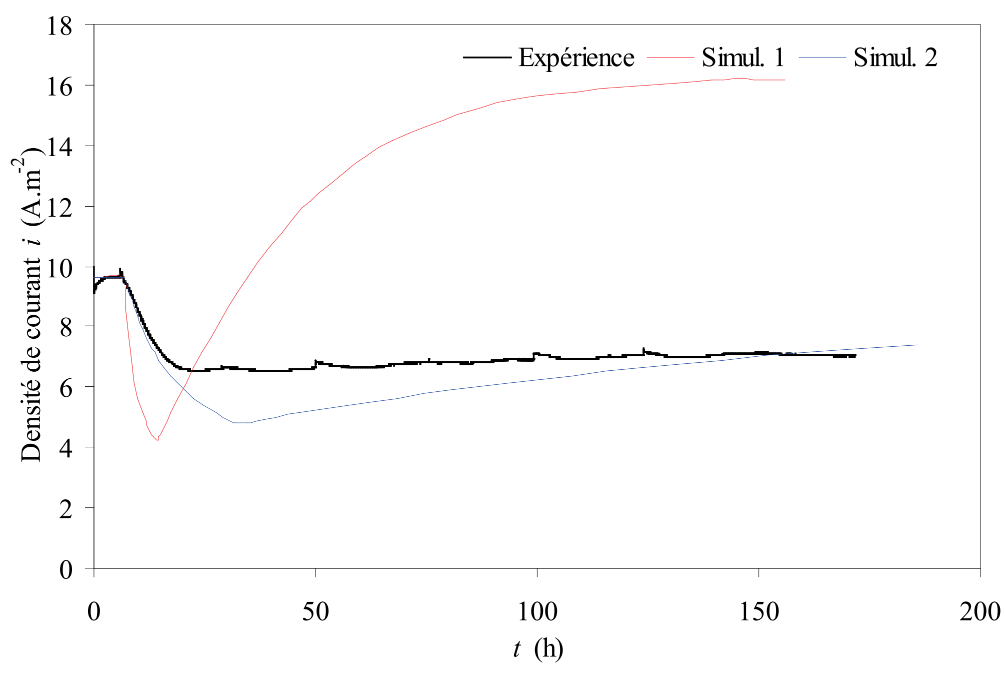
$$c_k = c_{PC} K_\pm$$

All transport equations: flux, balance et Current density, isotherms... *are influenced by the coefficients K+ or K-*

3. Modelling of ionic transport in saturated porous media

Multi-species Approach

Evolution of current density according time with in un mortar w/c = 0,5



Simul 1: whitout EDL

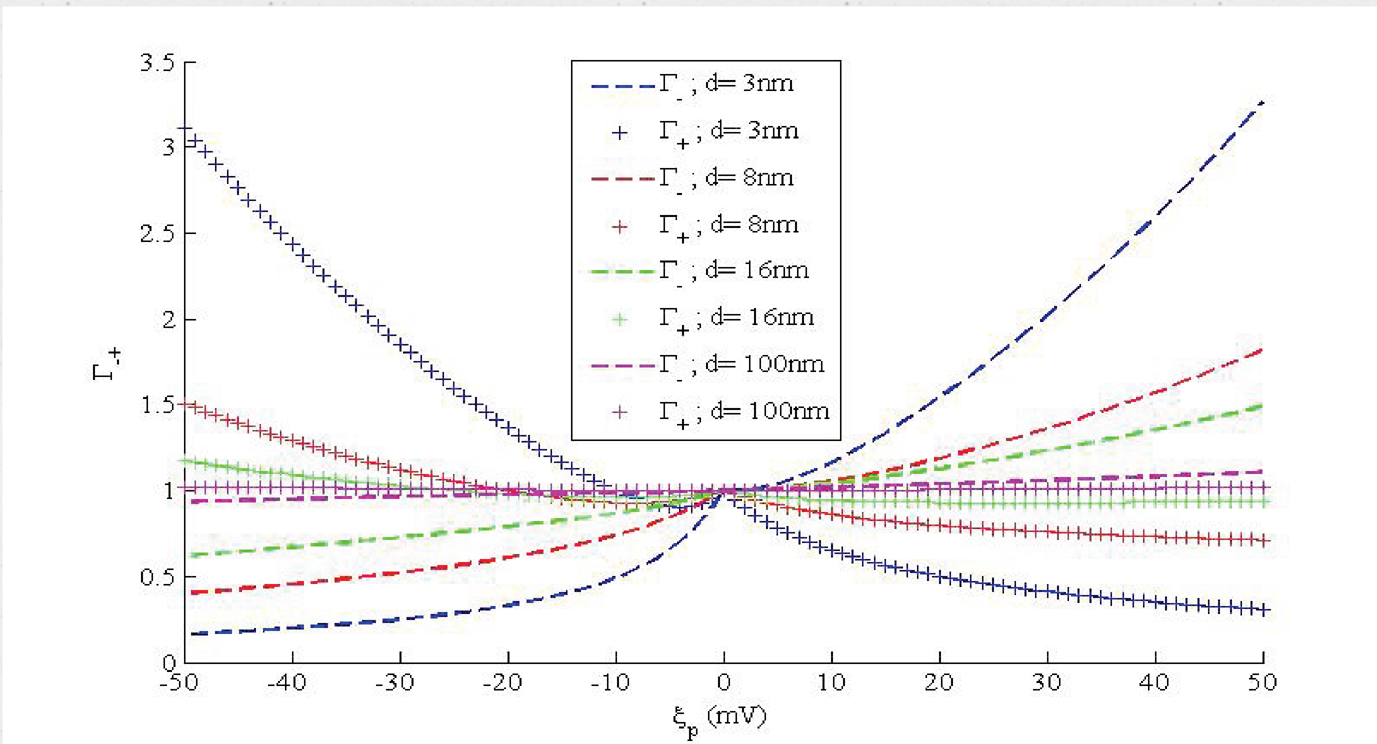
Simul 2: whith EDL

- **Confirmation of slowing down effect of EDL**
- **Decreasing of simulated current when the flux cation is corrected**

3. Modelling of ionic transport in saturated porous media

EDL Effect : Two key parameters

- Zeta Potential : intensity of the induced potential
- Pore diameter: Overlapping



CONCLUSION

- **Phenomenological approach: why not as first step, for comparison**
- **Evolution of Electrical current allows to explain some phenomena**
- **Electrical double layer effect : Pore size and Zeta Potential**
- **Consideration of more realistic pore network.**

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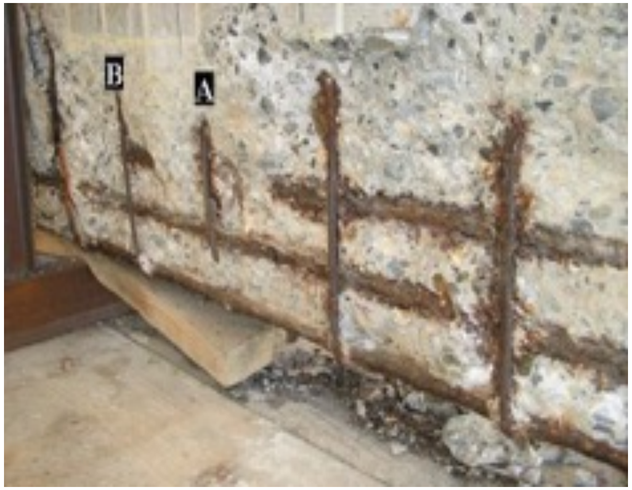
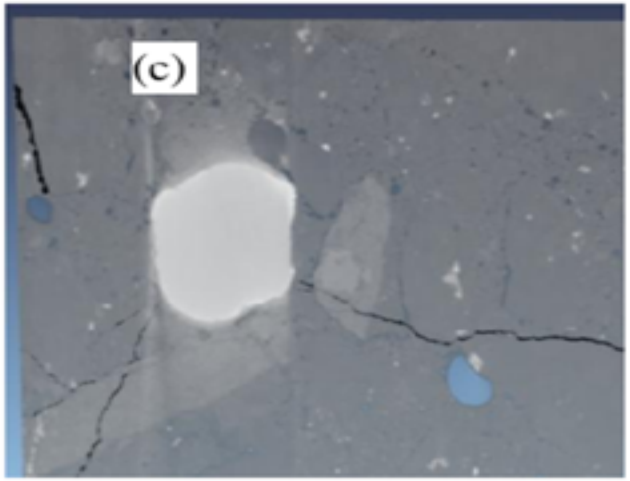
Numerical Analysis of Crack-Induced Diffusivity of Cement Paste though Phase-Fielding Modeling Coupled with Diffusion

Tao Wu - Technische Universität Braunschweig, Germany
Laura De Lorenzis - Technische Universität Braunschweig, Germany



Chloride diffusion – Corrosion of steel



Cracking accelerates chloride diffusion

Jin et al. (2014)

Objective: modeling effects of cracks on chloride diffusion

Model Review

Models	Limitations	References
Analytical Models	Highly simplified	Bentz et al. (1999)
Artificial Cracks	Not realistic cracking phenomenon, no coupling with mechanical field	Bentz and Garboczi (1998) Martin-Perez et al. (2000)
Continuum Damage Model	Mesh sensitivity, phenomenological formulation	Wang and Ueda (2009) Nilenius et al. (2014, 2015)
Cohesive Zone Model	Crack path known a priori, difficulty in obtaining parameters of interface	Carol et al. (2004), Wu and Wriggers (2015)
Lattice Model	Depending on crack criteria	Savija et al. (2010),

Objective : phase field cracking model coupled with diffusion

Outline

- Introduction to Phase Field Modeling of Cracking
- Diffusion coupled with Phase Field Model
- Numerical Examples
- Multiscale Investigation on Concrete
- Conclusions and Outlook

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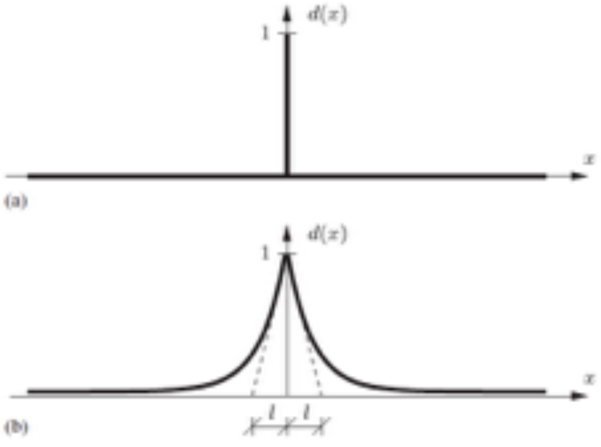
Numerical Example : Single Edge-Notched Test



Diffusive Crack

$$\mathrm{div}\boldsymbol{\sigma} = 0 \qquad \boldsymbol{\sigma}(\boldsymbol{u}, s) := (s^2+\eta)\frac{\partial \Psi_0^+(\epsilon)}{\partial \epsilon} + \frac{\partial \Psi_0^-(\epsilon)}{\partial \epsilon}$$

$$G_c\left(2l\Delta s + \frac{1-s}{2l}\right) = 2s\mathcal{H}^+$$

$$\mathcal{H}^+ := \max_{\tau\in[0,t]} \Psi_0^+(\boldsymbol{\varepsilon}(\boldsymbol{x},\tau))$$

Phase Field Parameter

s=[0,1]

Amor et al. (2009)
Miehe et al. (2010)
Ambati et al. (2014)

Variational fracture formulation Francfort and Marigo (1998)

$$E(\boldsymbol{u},\Gamma) = \int_{\mathcal{B}_t} \Psi_0(\boldsymbol{\epsilon}(\boldsymbol{u}))\,\mathrm{d}\boldsymbol{x} + G_c \int_{\partial\mathcal{B}_t} \mathrm{d}s$$

Regularization Bourdin et al. (2000)

$$E(\boldsymbol{u},s) = (s^2+\eta)\int_{\mathcal{B}_t} \Psi_0(\boldsymbol{\epsilon}(\boldsymbol{u}))\,\mathrm{d}\boldsymbol{x} + G_c \int_{\mathcal{B}_t} \left(\frac{1}{4l}(1-s)^2 + l|\nabla s|^2\right)\mathrm{d}\boldsymbol{x}$$

Advantage

- Elegant mathematical background
- Describe the three-dimensional crack behaviors without introducing any additional ad-hoc criteria and without the need of using remeshing strategies
- Few parameters in the model

Disadvantage

- Very fine mesh in the critical zone

Amor et al. (2009)
Miehe et al. (2010)
Ambati et al. (2014)

Outline

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Numerical Example : Single Edge-Notched Test

Gurtin's framework
Gurtin et al. (2013)

Internal power $\mathcal{P} = \int_{\mathcal{B}_t} \boldsymbol{\sigma} : \dot{\boldsymbol{\epsilon}} \, \mathrm{d}v + \int_{\mathcal{B}_t} \xi \cdot \nabla \dot{s} \, \mathrm{d}v + \int_{\mathcal{B}_t} \zeta \cdot \dot{s} \, \mathrm{d}v$

External power $\mathcal{W} = \int_{\partial\mathcal{B}_t} \boldsymbol{t} \cdot \dot{\boldsymbol{u}} \, \mathrm{d}a + \int_{\mathcal{B}_t} \boldsymbol{b} \cdot \dot{\boldsymbol{u}} \, \mathrm{d}v + \int_{\partial\mathcal{B}_t} \mathcal{X} \dot{s} \, \mathrm{d}a + \int_{\mathcal{B}_t} \mathcal{R} \dot{s} \, \mathrm{d}v$

Principle of virtual power $\mathcal{W} = \mathcal{P}$

Macroscopic force balance $\mathrm{div} \boldsymbol{\sigma} = 0$

Phase Field microscopic force balance $\mathrm{div} \xi + \zeta + \mathcal{R} = 0$

Mass balance $\dot{c} = -\mathrm{div} \boldsymbol{h} + h$

Numerical Example : Single Edge-Notched Test

Free-energy imbalance $\int_{\mathcal{B}_t} \dot{\psi}\, \mathrm{d}v \leq \mathcal{W} + \mathcal{T}$

Power through transport $\mathcal{T} = -\int_{\partial\mathcal{B}_t} \mu \boldsymbol{h} \cdot \boldsymbol{n}\, \mathrm{d}a + \int_{\mathcal{B}_t} \mu h\, \mathrm{d}v$

Total free-energy $\Psi = \Psi(\boldsymbol{\epsilon}, c, s, \nabla s)$

Local dissipation inequality $\dot{\Psi} - \boldsymbol{\sigma} : \dot{\boldsymbol{\epsilon}} - \xi \cdot \nabla \dot{s} - \zeta \dot{s} - \mu \dot{c} + \boldsymbol{h} \cdot \nabla \mu \leq 0$

$$\Rightarrow \quad \boldsymbol{\sigma} = \frac{\partial \Psi}{\partial \boldsymbol{\epsilon}} \qquad \mu = \frac{\partial \Psi}{\partial c} \qquad \xi = \frac{\partial \Psi}{\partial s} \qquad \zeta = \frac{\partial \Psi}{\partial \nabla s}$$

Evolution of phase field $\mathrm{div}\left(\frac{\partial \Psi}{\partial \nabla s}\right) - \frac{\partial \Psi}{\partial s} = 0$

Reduced dissipation inequality $\boldsymbol{h} \cdot \nabla \mu \leq 0 \qquad \boldsymbol{h} = -\boldsymbol{D} \nabla \mu$

- Isotropic $D \geq 0$
- Anisotropic $\boldsymbol{D}$ positive semi-definite

Numerical Example : Single Edge-Notched Test

Free-energy imbalance $\int_{\mathcal{B}_t} \dot{\psi} \, \mathrm{d}v \leq \mathcal{W} + \mathcal{T}$

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⇒ $\boldsymbol{\sigma} = \frac{\partial \Psi}{\partial \boldsymbol{\epsilon}} \quad \mu = \frac{\partial \Psi}{\partial c} \quad \xi = \frac{\partial \Psi}{\partial s} \quad \zeta = \frac{\partial \Psi}{\partial \nabla s}$

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Reduced dissipation inequality $\boldsymbol{h} \cdot \nabla \mu \leq 0 \quad \boldsymbol{h} = -\boldsymbol{D} \nabla \mu$

- Isotropic $D \geq 0$
- Anisotropic $\boldsymbol{D}$ positive semi-definite

Numerical Example : Single Edge-Notched Test

Options for coupling

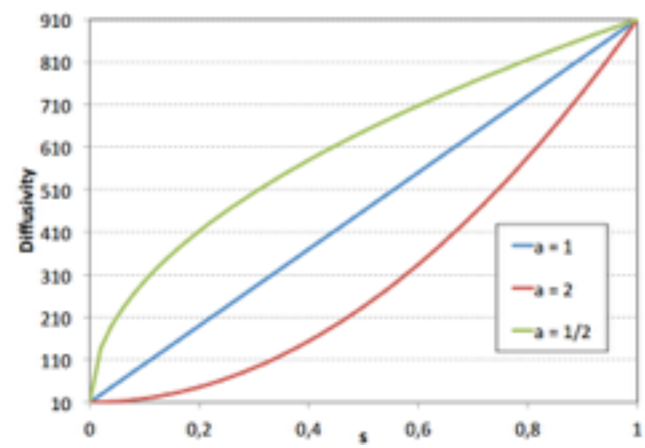
(1) Source term : one-way coupling
diffusion → crack

(2) $\Psi_{\mathrm{dif}}(c,s)$ instead of $\Psi_{\mathrm{dif}}(c)$
two-way coupling
diffusion ↔ cracking

(3) $D(s)$ one-way coupling
cracking → diffusion

(4) Combination of (1) and (3)

$$D(s) = (1 - s^a)D_0 + s^a D_1$$



Outline

- Introduction to Phase Field Modeling of Cracking
- Diffusion coupled with Phase Field Model
- Analytical Solution of One-Dimensional Bar
- Numerical Examples
- Multiscale Investigation on Concrete
- Conclusions and Outlook

Homogenization

Isotropic Material

$\boldsymbol{h} = -D(s)\nabla c$ Fick's Law

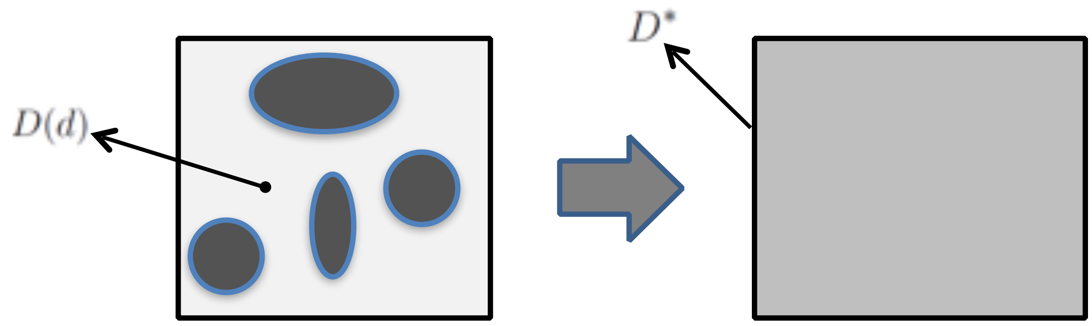
Effective Constitutive Law

$$\boldsymbol{h}^*(\langle\nabla c\rangle) = -D^*\langle\nabla c\rangle$$

$$\Pi := [\langle\boldsymbol{h}\rangle - \boldsymbol{h}^*(\langle\nabla c\rangle)]^2 \quad \rightarrow \quad \min$$

$$\frac{\mathrm{D}\Pi}{\mathrm{d}D^*} \stackrel{!}{=} 0$$

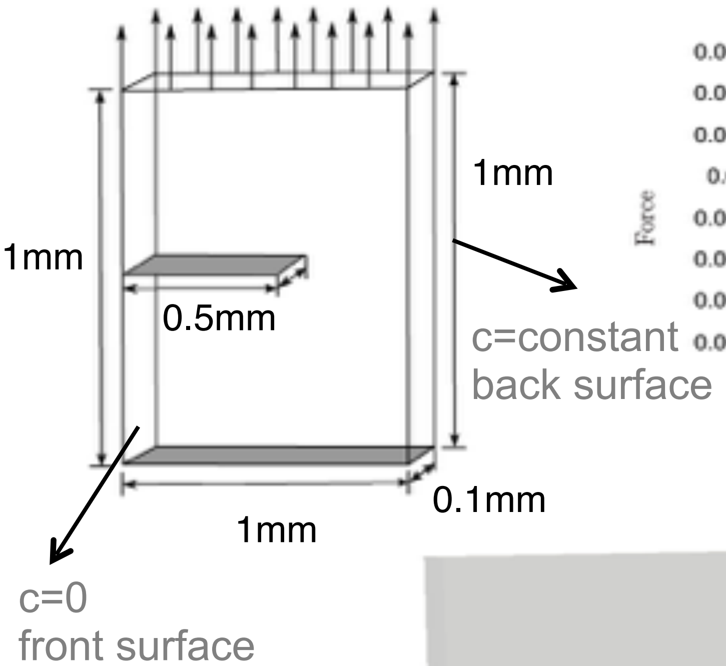
$$D^* = -\frac{\langle h\rangle_1\langle\nabla c\rangle_1 + \langle h\rangle_2\langle\nabla c\rangle_2 + \langle h\rangle_3\langle\nabla c\rangle_3}{\langle\nabla c\rangle_1^2 + \langle\nabla c\rangle_2^2 + \langle\nabla c\rangle_3^2}$$

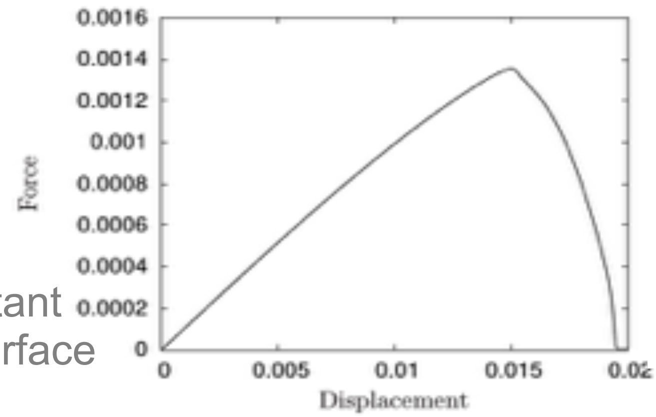


- Post-processing
- Better comparison with experiment

Hain et al. (2008), Wu et al. (2013)

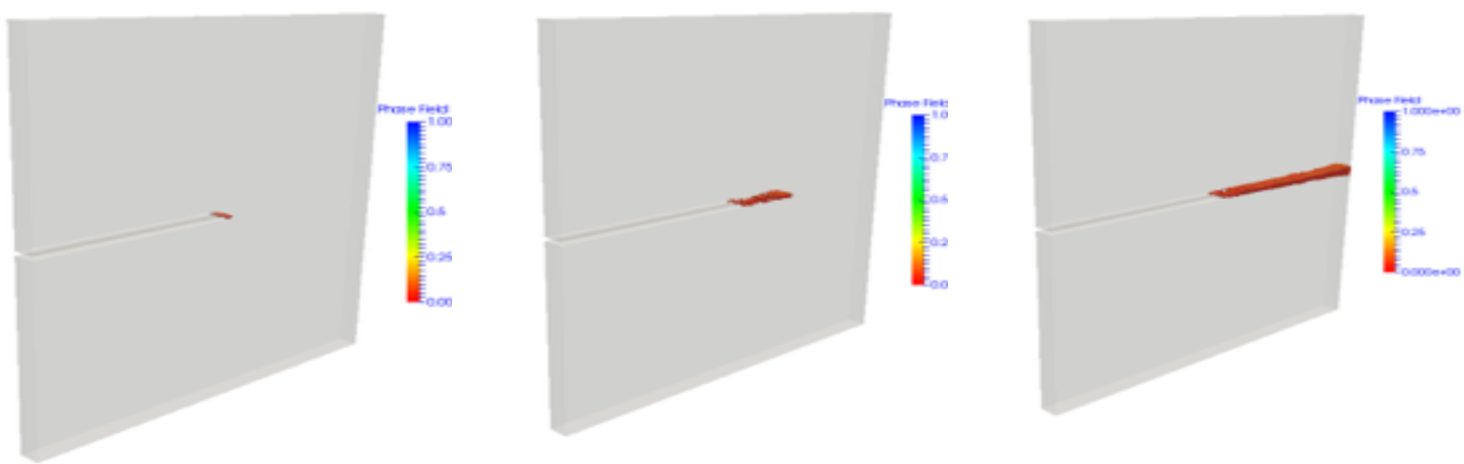
Numerical Example : Single Edge-Notched Test



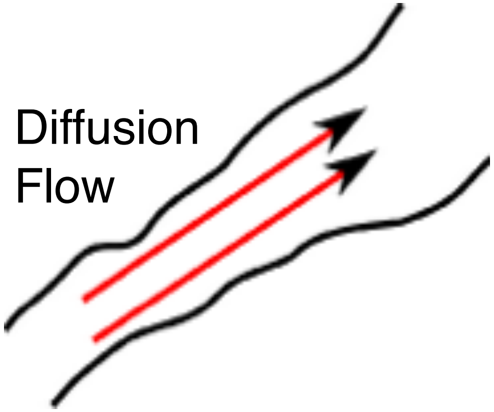


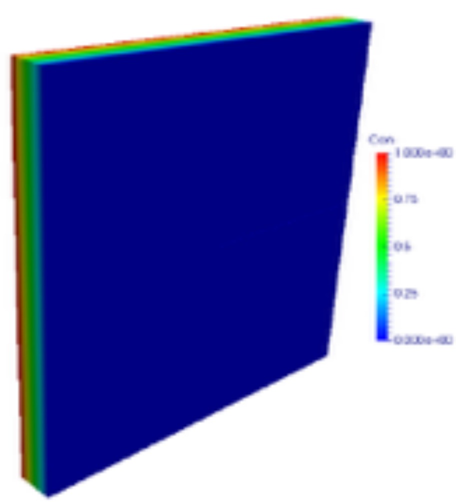
Property	Value
E	$17730\ N/mm^2$
ν	0.21
G_c	$2.1* \times 10^{-3} kN/mm$
l	0.01
D_0	$1.5 \times 10^{-12} m^2/s$
D_1	$2000 \times 10^{-12} m^2/s$

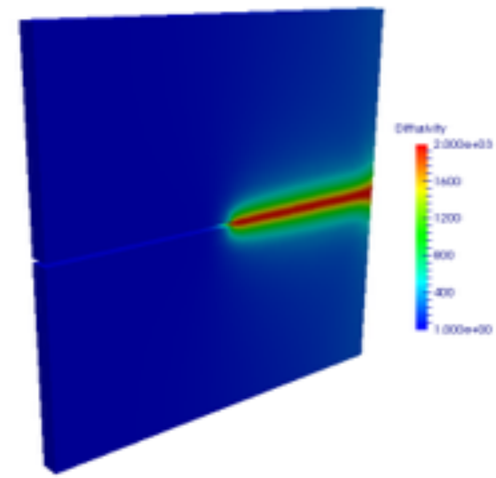
Bentz et al. (2015)

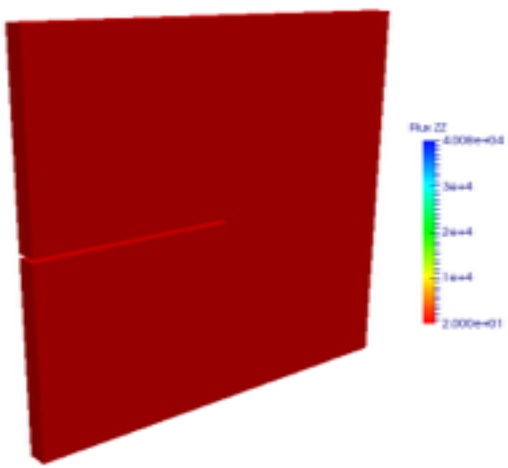


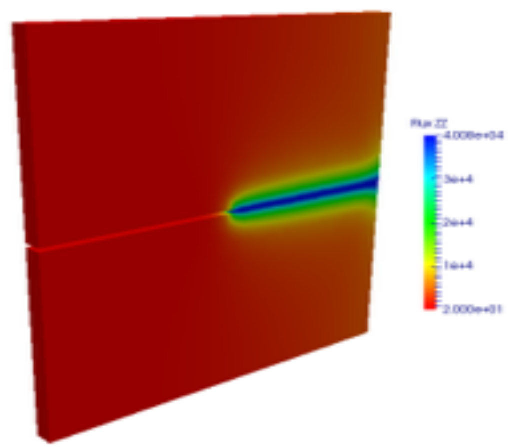
Numerical Example : Single Edge-Notched Test



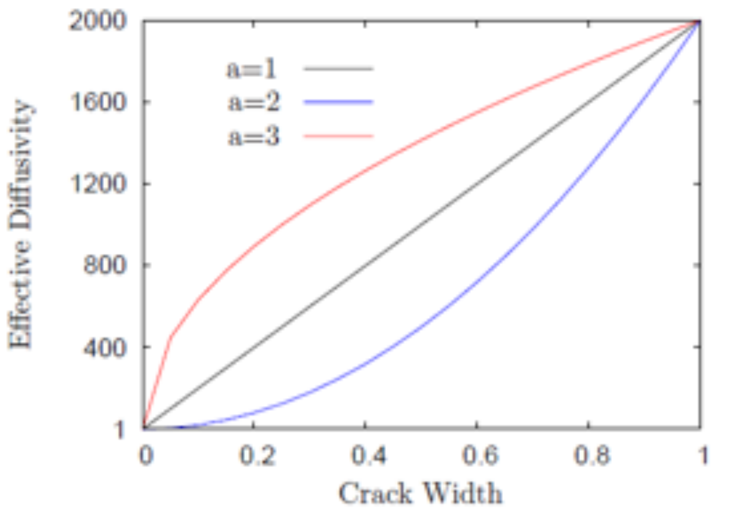


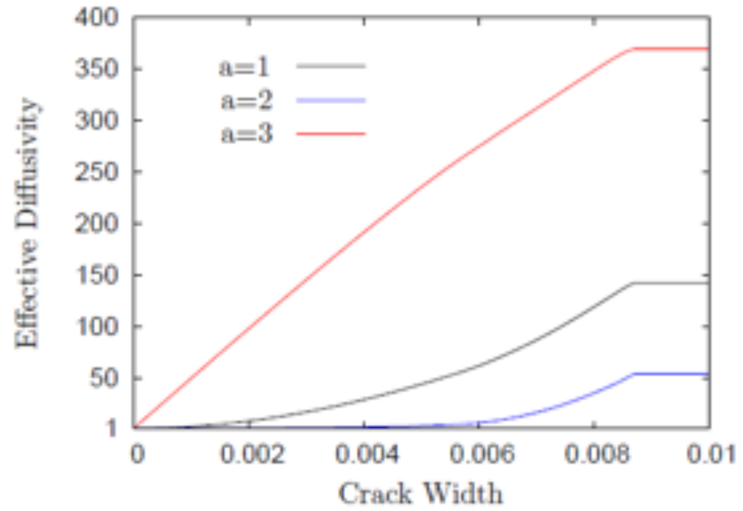






Numerical Example : Single Edge-Notched Test



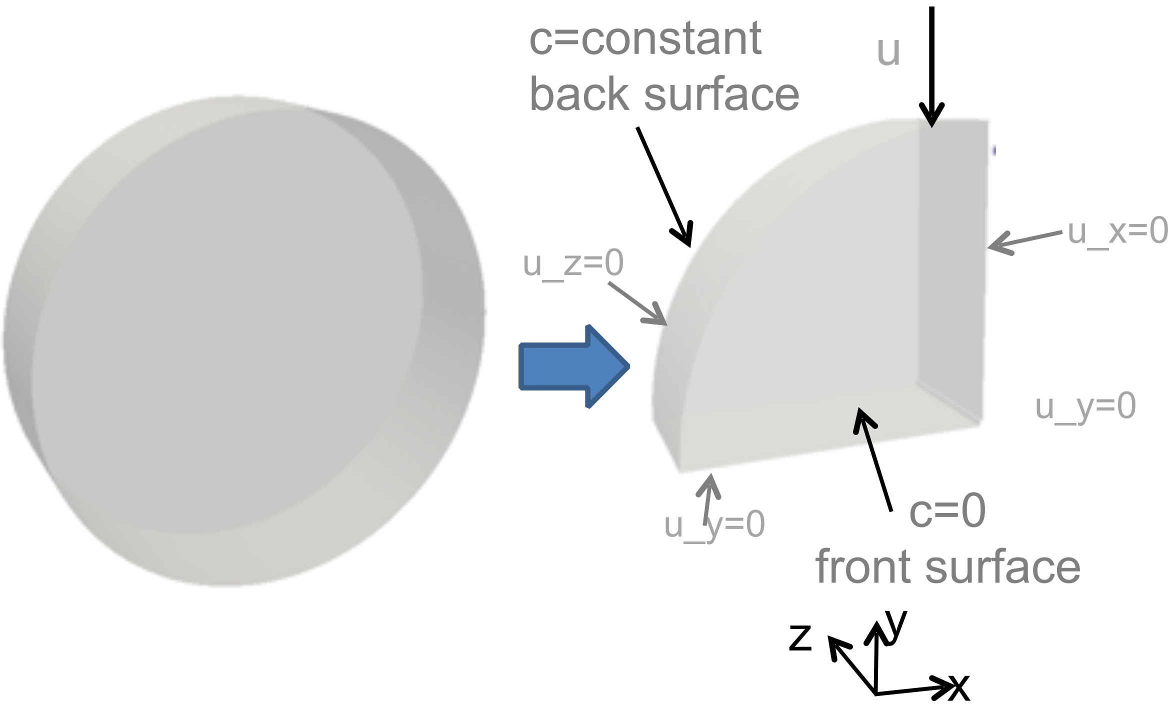


$$D(s) = (1 - s^a)D_0 + s^a D_1$$

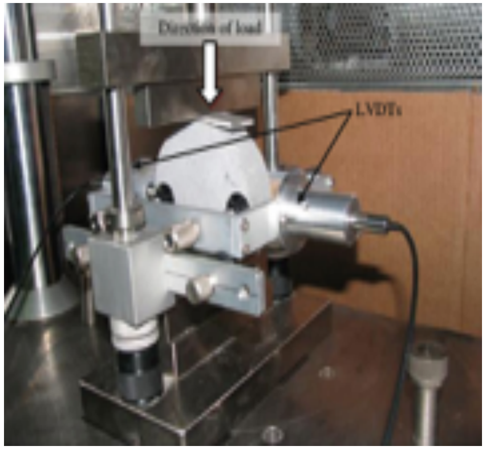
Bentz et al. (2015)

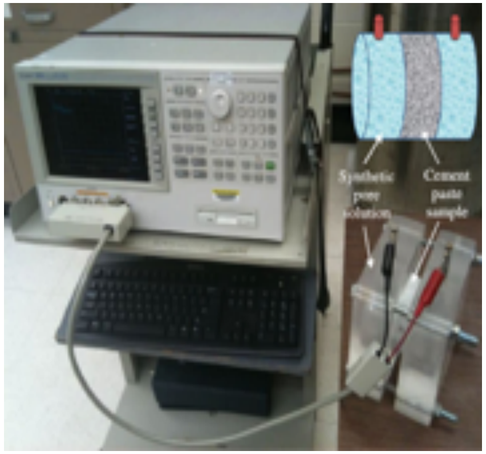
- D_0 Diffusivity of intact material
- D_1 Diffusivity of fully broken material

Numerical Example : Brazilian Test



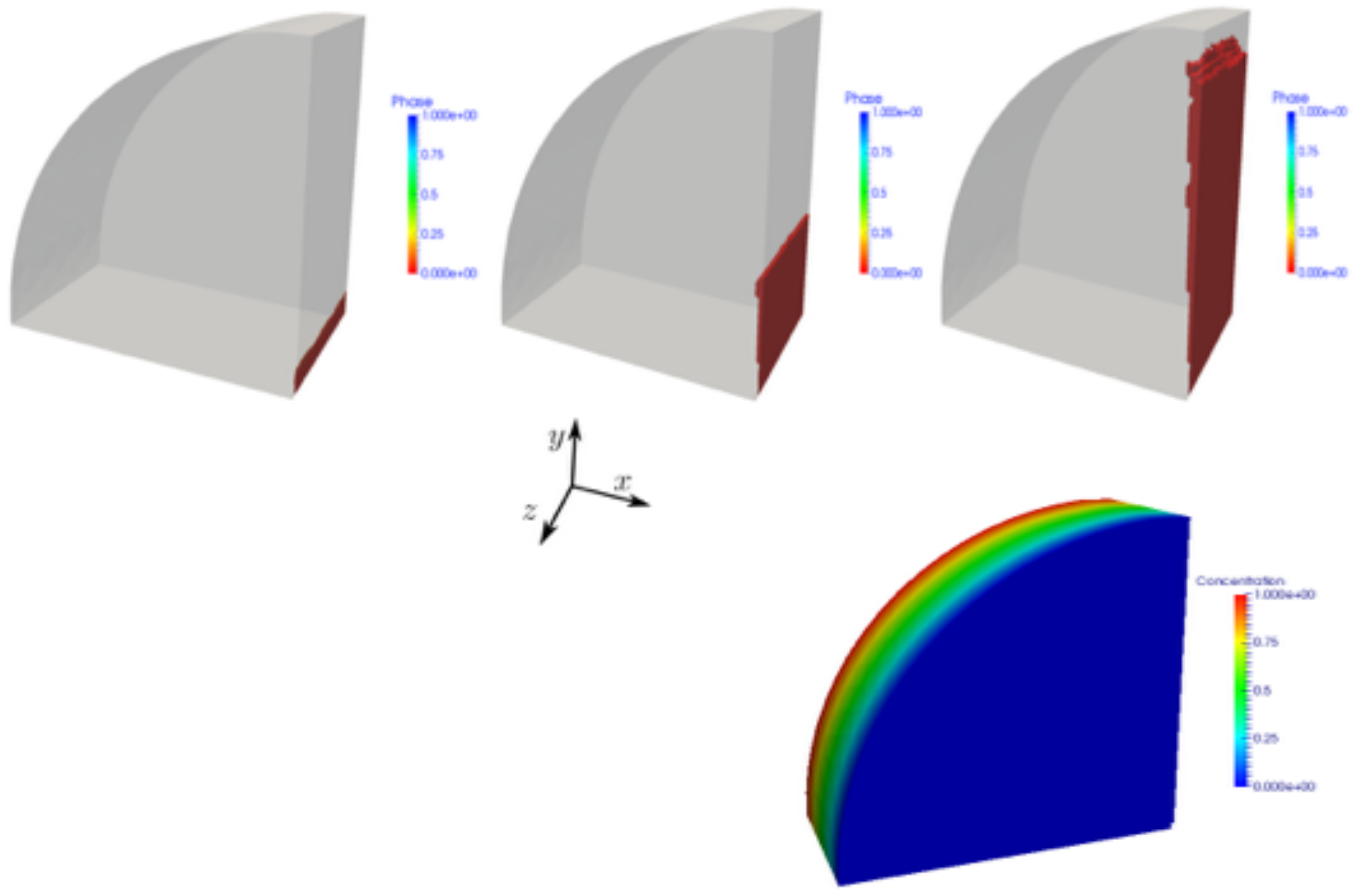
Brazilian Test





Akhavan et al. (2013)

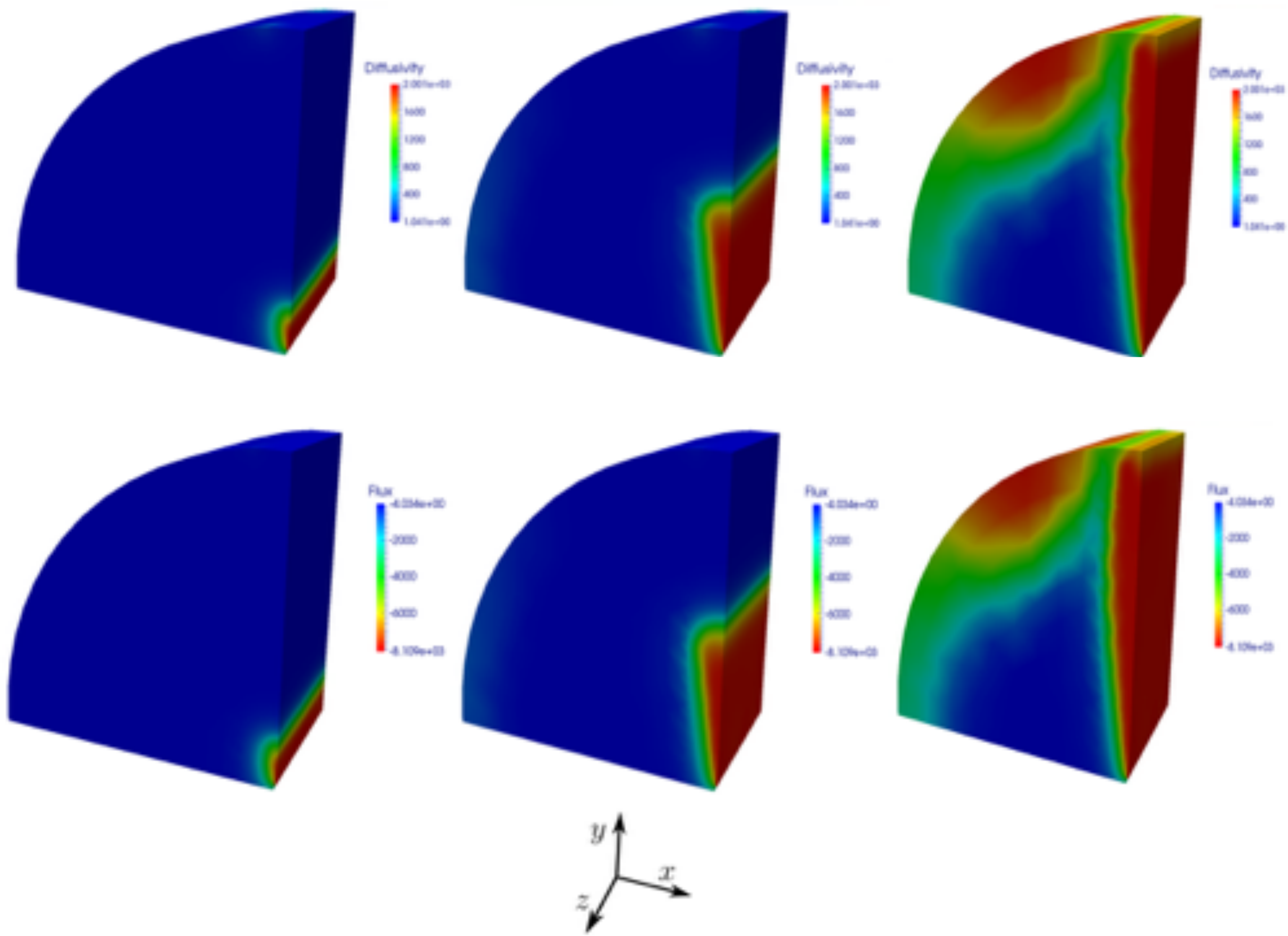
Numerical Example : Brazilian Test



Numerical Example : Brazilian Test

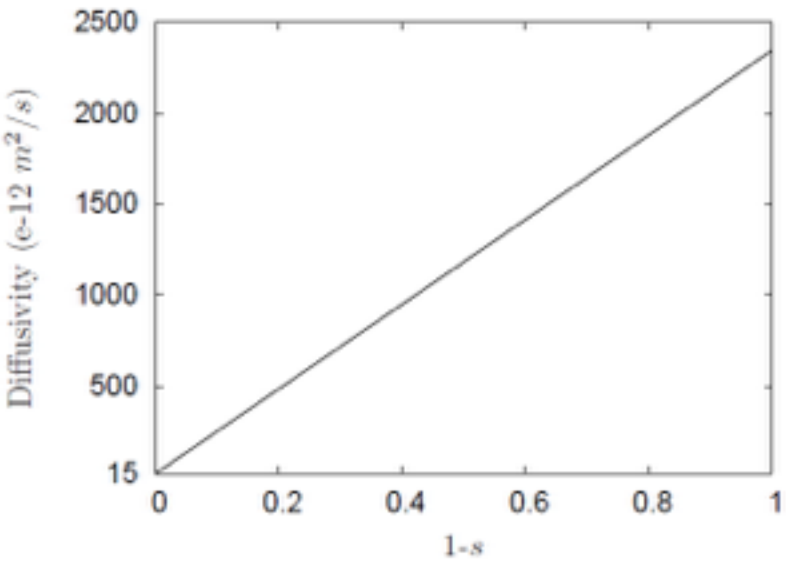
Diffusivity

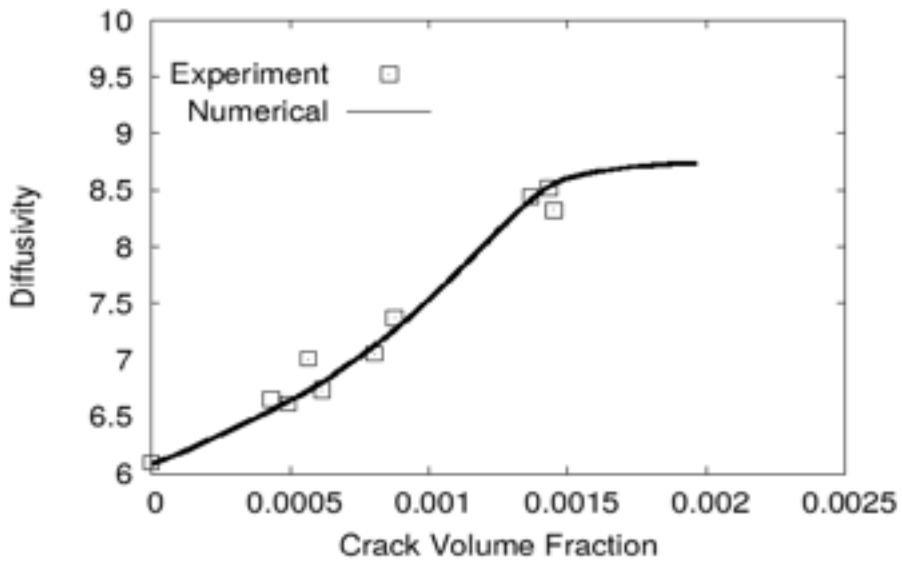
Flux



Numerical Example : Brazilian Test

Parameter Identification



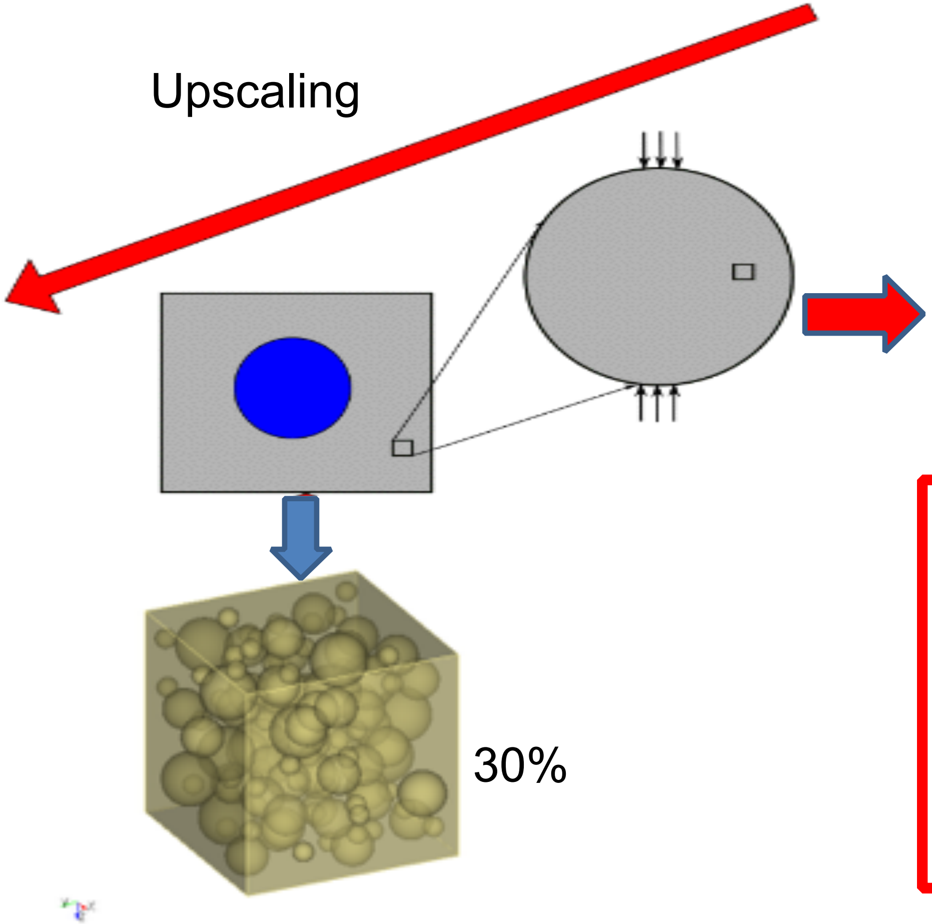


Local Diffusivity-Phase Field

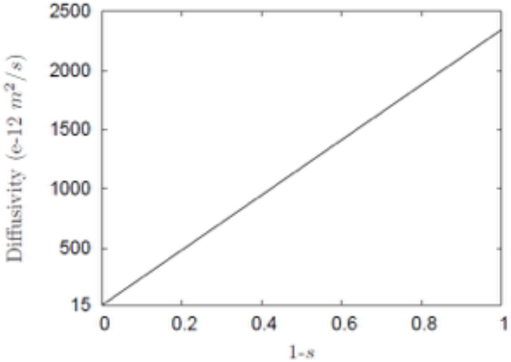
Outline

- Introduction to Phase Field Modeling of Cracking
- Diffusion coupled with Phase Field Model
- Analytical Solution of One-Dimensional Bar
- Numerical Examples
- Multiscale Investigation on Concrete
- Conclusions and Outlook

Multiscale Framework



Local diffusivity-phase field

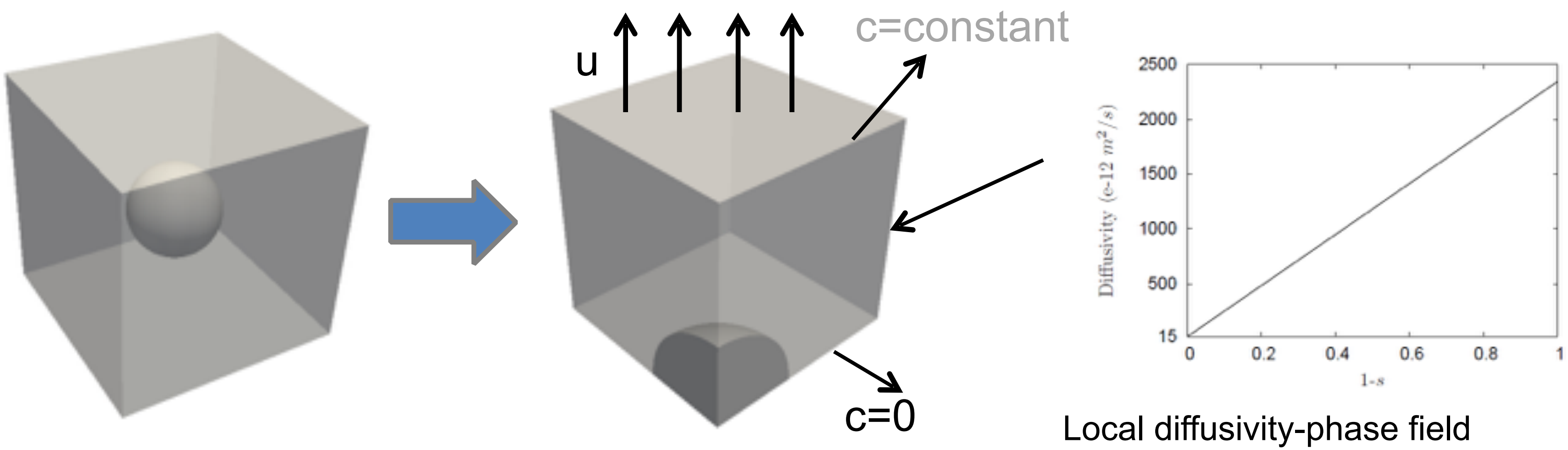


Mesoscale of Concrete

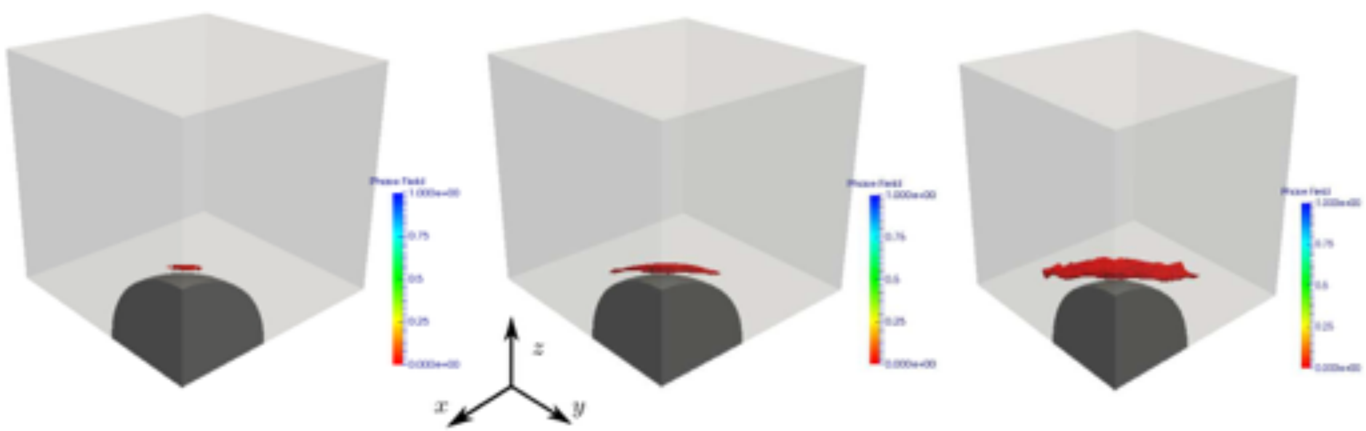
Take-Place Approach

Wriggers and Moftah (2005)
Hafner et al. (2006)
Wu et al. (2013)

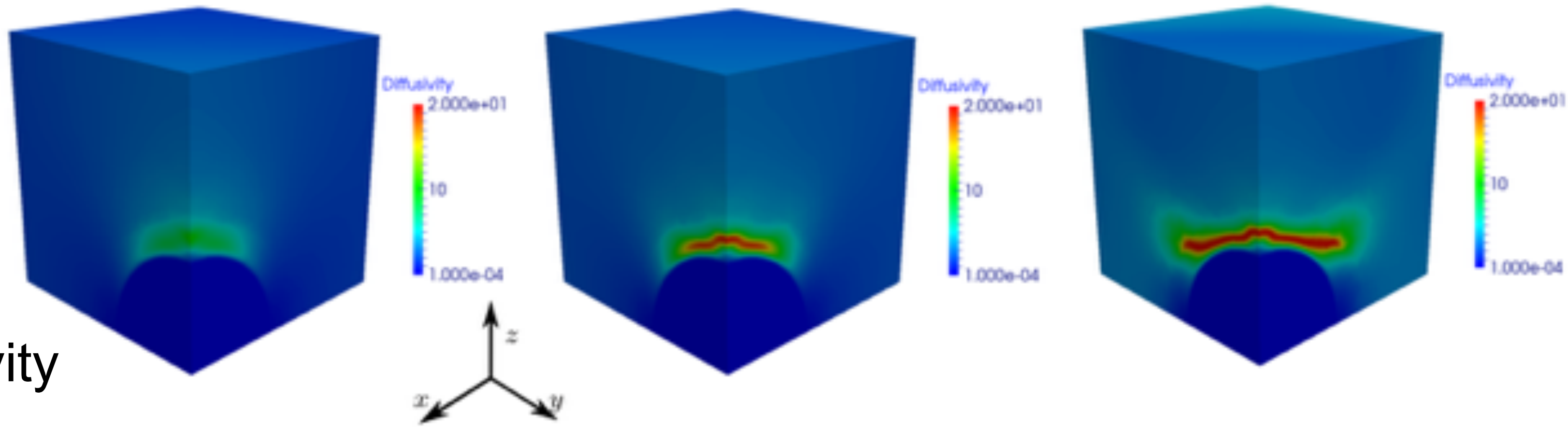
Numerical Example : Unit Cell



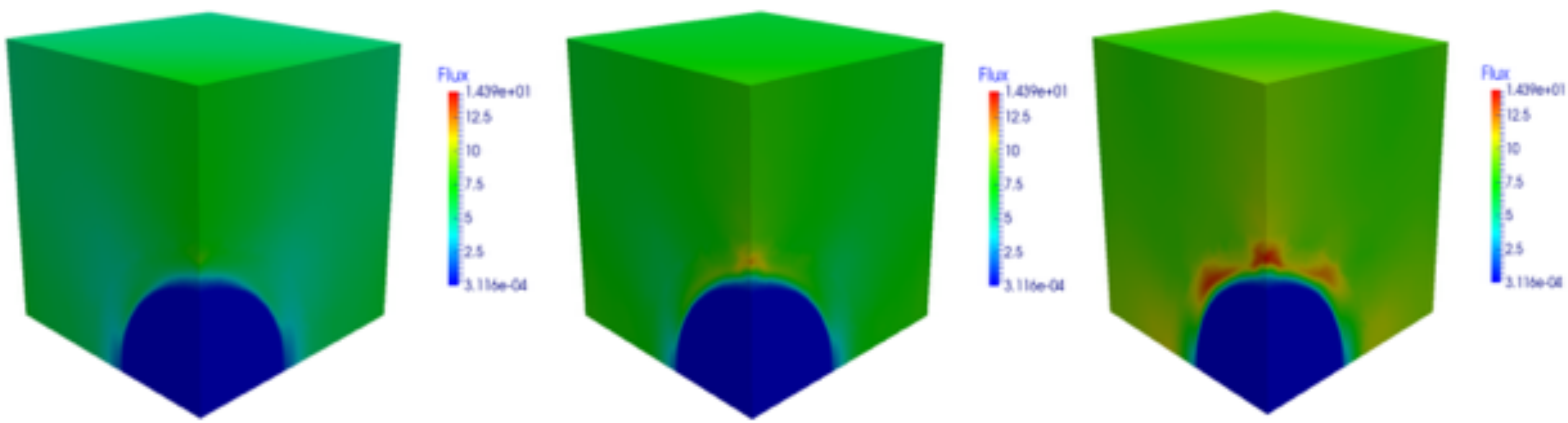
Local diffusivity-phase field



Numerical Example : Unit Cell

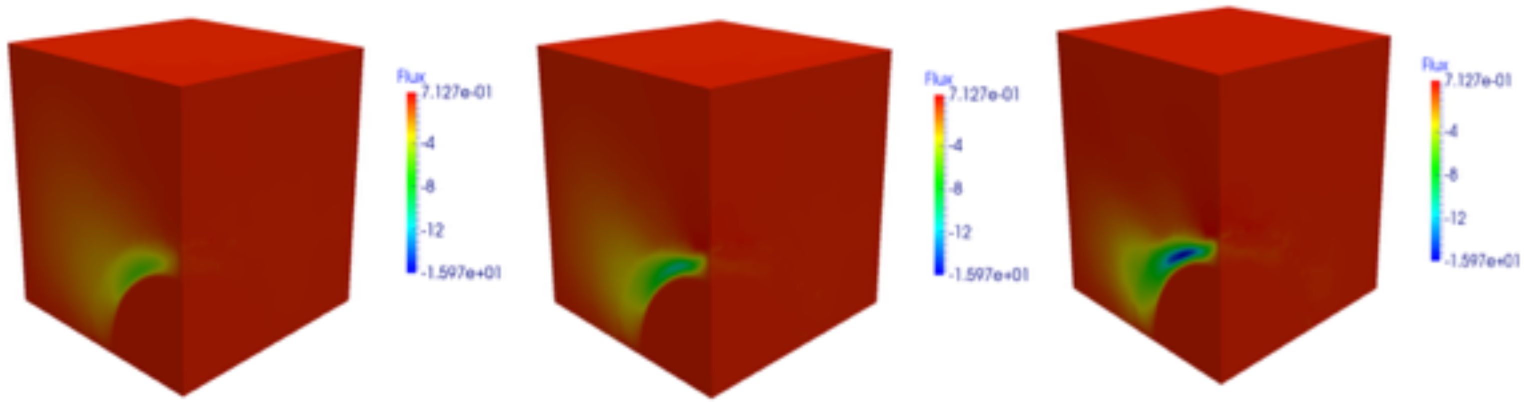


Diffusivity

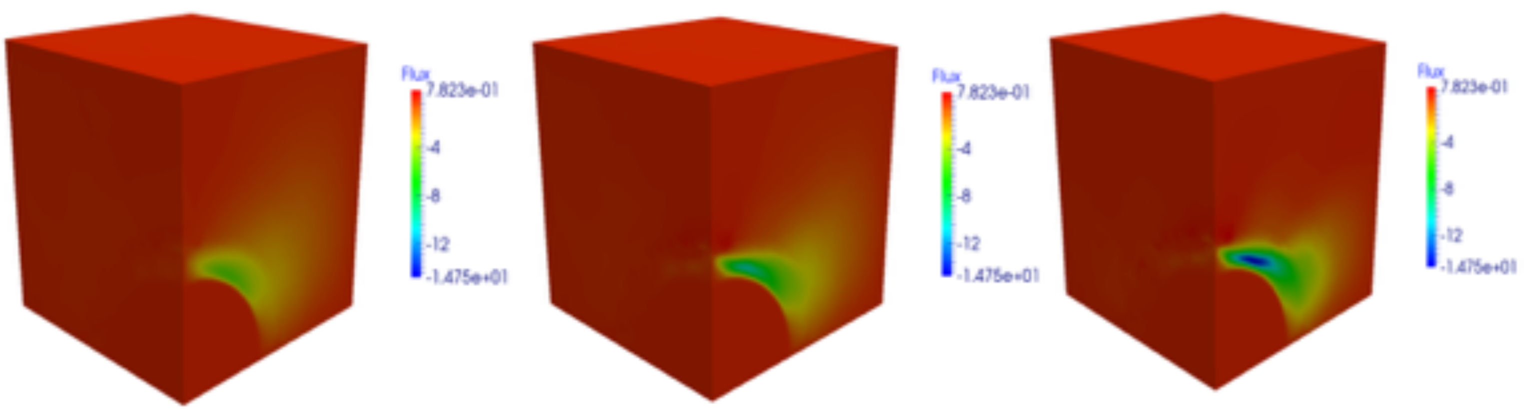


Flux in z direction

Numerical Example : Unit Cell

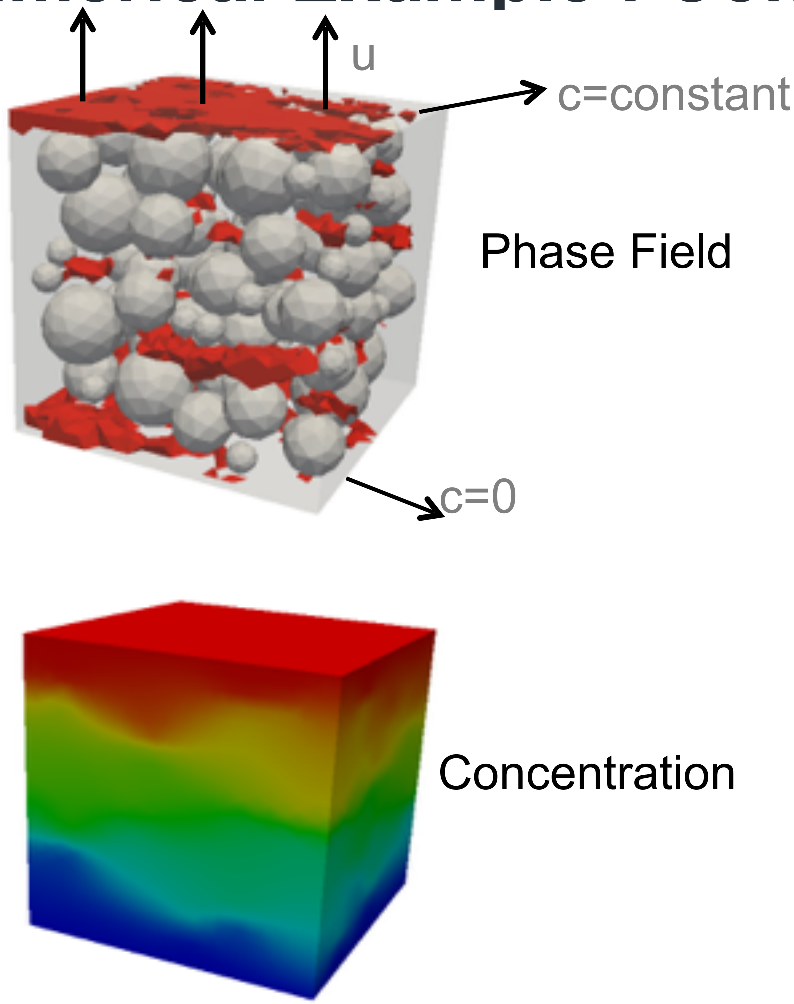


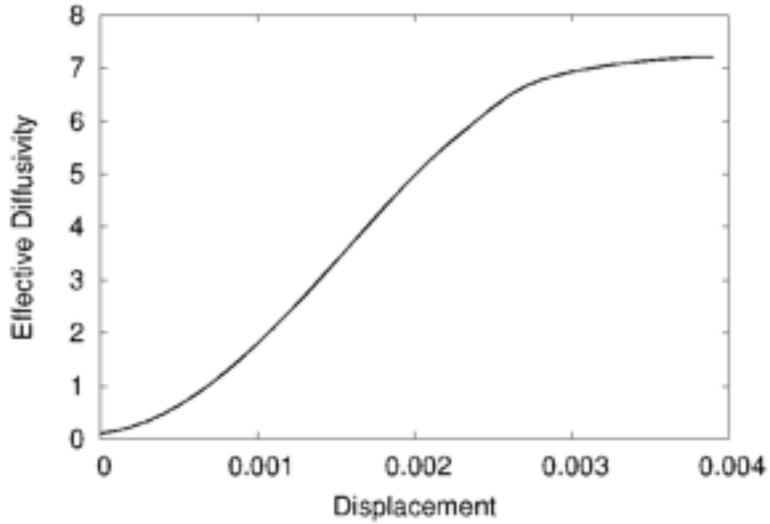
Flux in x direction



Flux in y direction

Numerical Example : Concrete





Conclusions

- Phase field model of cracking coupled with diffusion
- Numerical results compared with experiments
- Multiscale framework set-up

Outlook

- Anisotropic diffusion
- Diffusion accompanying with reaction: internal source term
- Cracks induced by corrosion of chloride ions

TU 1404

COST ACTION

Back to the list of presentations

TU1404 COST ACTION

STATUS OF THE RRT+

Gregor Trtnik – Igmat Building Materials Institute, Slovenia
Stephanie Staquet - Université Libre de Bruxelles, Belgium
Dirk Schlicke - Graz University of Technology, Austria
Marijana Serdar – University of Zagreb, Croatia
Miguel Azenha - University of Minho, Portugal

About RRT+ (please read RRT+ document!)

- **RRT+** - extended round robin testing programme due to the nature of this RRT (testing of difference advanced testing techniques, developing of „modified advanced“ concrete mixtures)
- RRT+ is divided into three different ways:

1) DIV 1: division according to main objectives of RRT+ (design phase, initial experimental phase, main experimental phase, additional experimental phase)

2) DIV 2: division according to the materials used to perform necessary experiments: level 0 – reference concrete mixtures, level 1 – sustainable and inovative CBM compositions (Stephanie Staquet, level 2 – modification of reference mixtures with the objective to show the ability of advanced testing techniques to detect such changes)

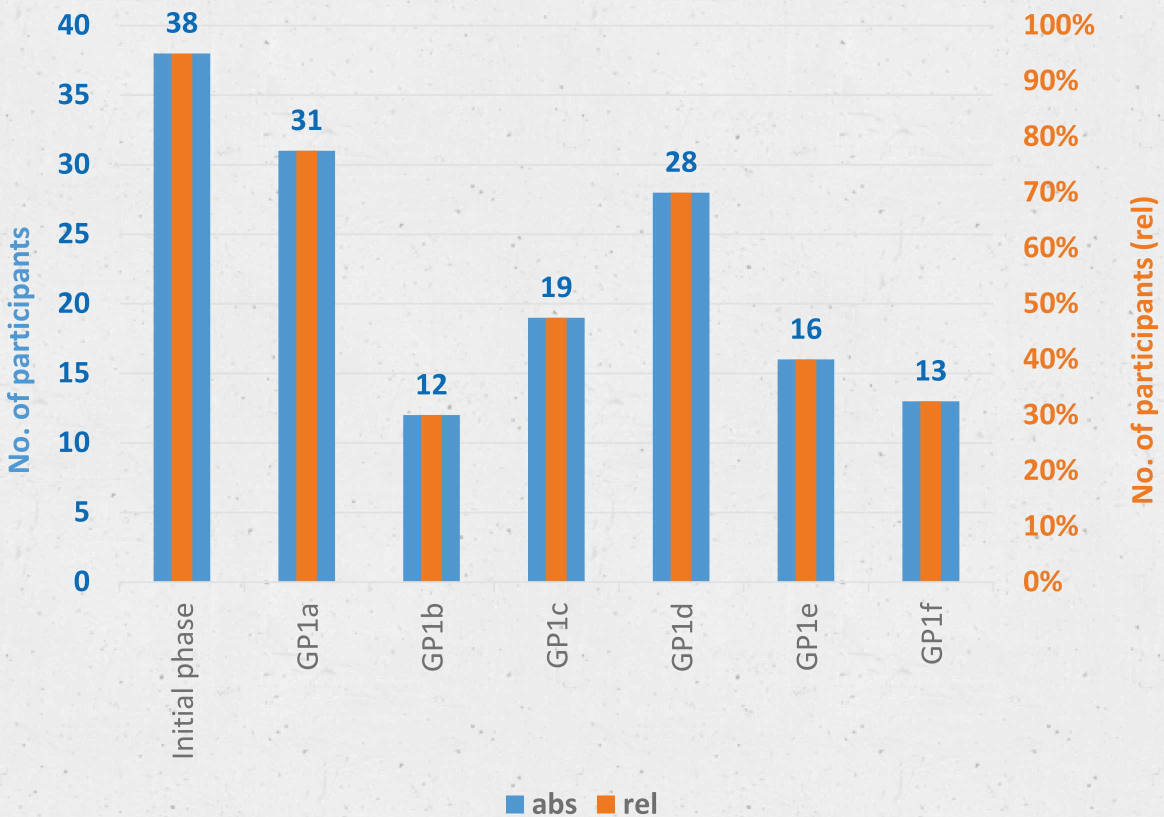
3) DIV 3: division according to the interest of the participants: type A (interested in using advanced testing technique), type B (interested in advanced concrete mixtures)

Design phase of RRT+ document

- **The design phase of RRT+ is finished.**
- **Objectives:**
  - to prepare RRT+ document entitled „*Instruction for participation*“, with all the instructions necessary to perform all the experiments
  - to collect „*letters of commitment*“ from all interested organizations (> 40 letter of commitment have been received)
  - to prepare a list of experimental procedures each interested laboratory wants to perform
  - to collect the amount of basic materials needed for each testing laboratory to perform the desired experiements
  - to organize transportaion of the materials from EDF (France) to national contact points of each country.

SUMMARY (STATISTISTICS) OF RRT+

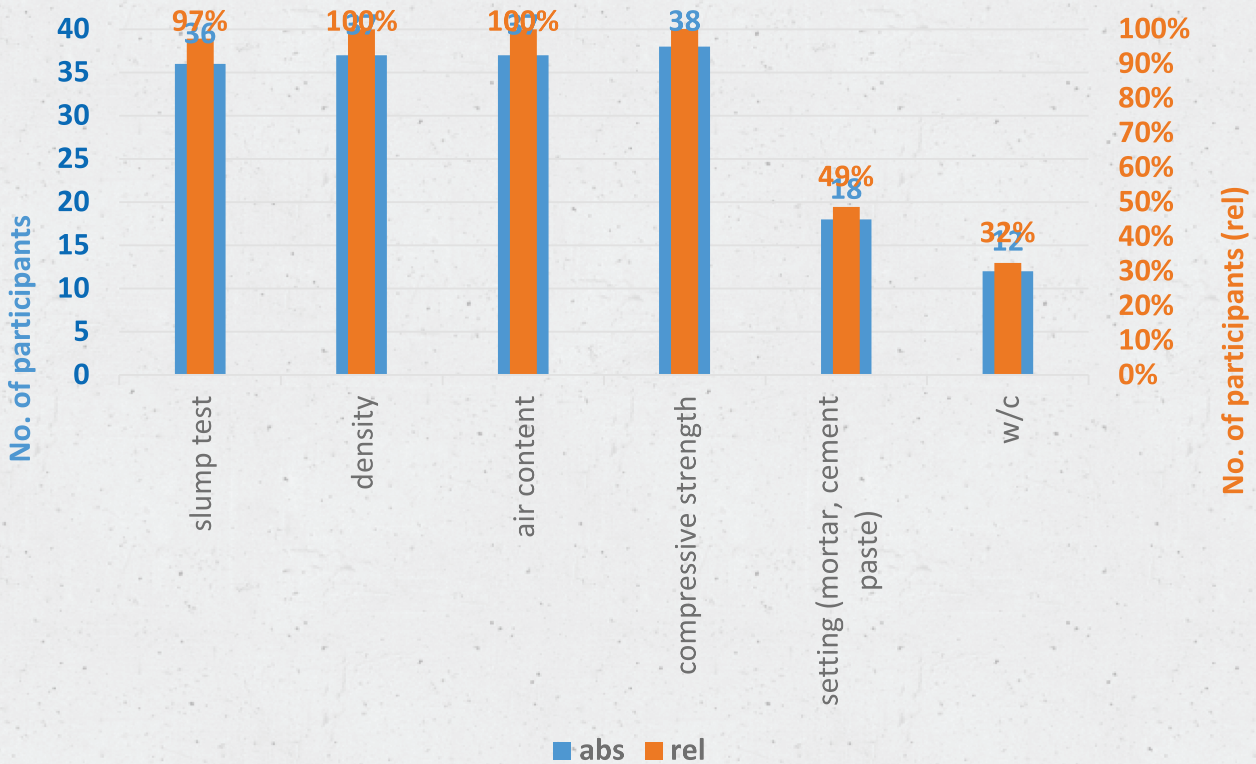
Participants interested in a specific GP1



- Winner: GP1a

SUMMARY (STATISTISTICS) OF RRT+

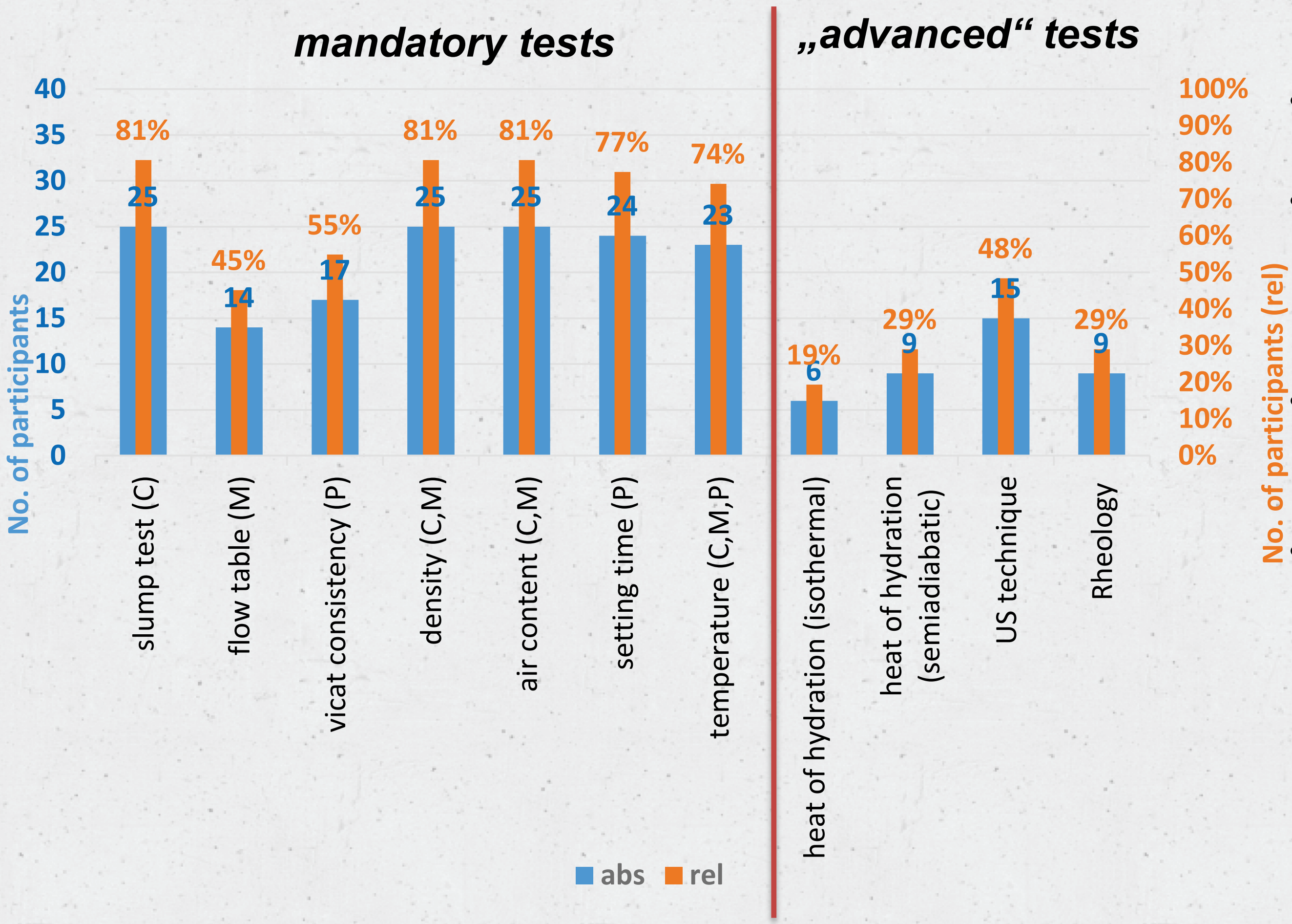
Participants interested in initial experimental phase



- **No. of interested organizations:** 38
- **% of participants interested in mandatory test:** 100%
- **% of participants interested in additional tests:** 32-48%

SUMMARY (STATISTISTICS) OF RRT+

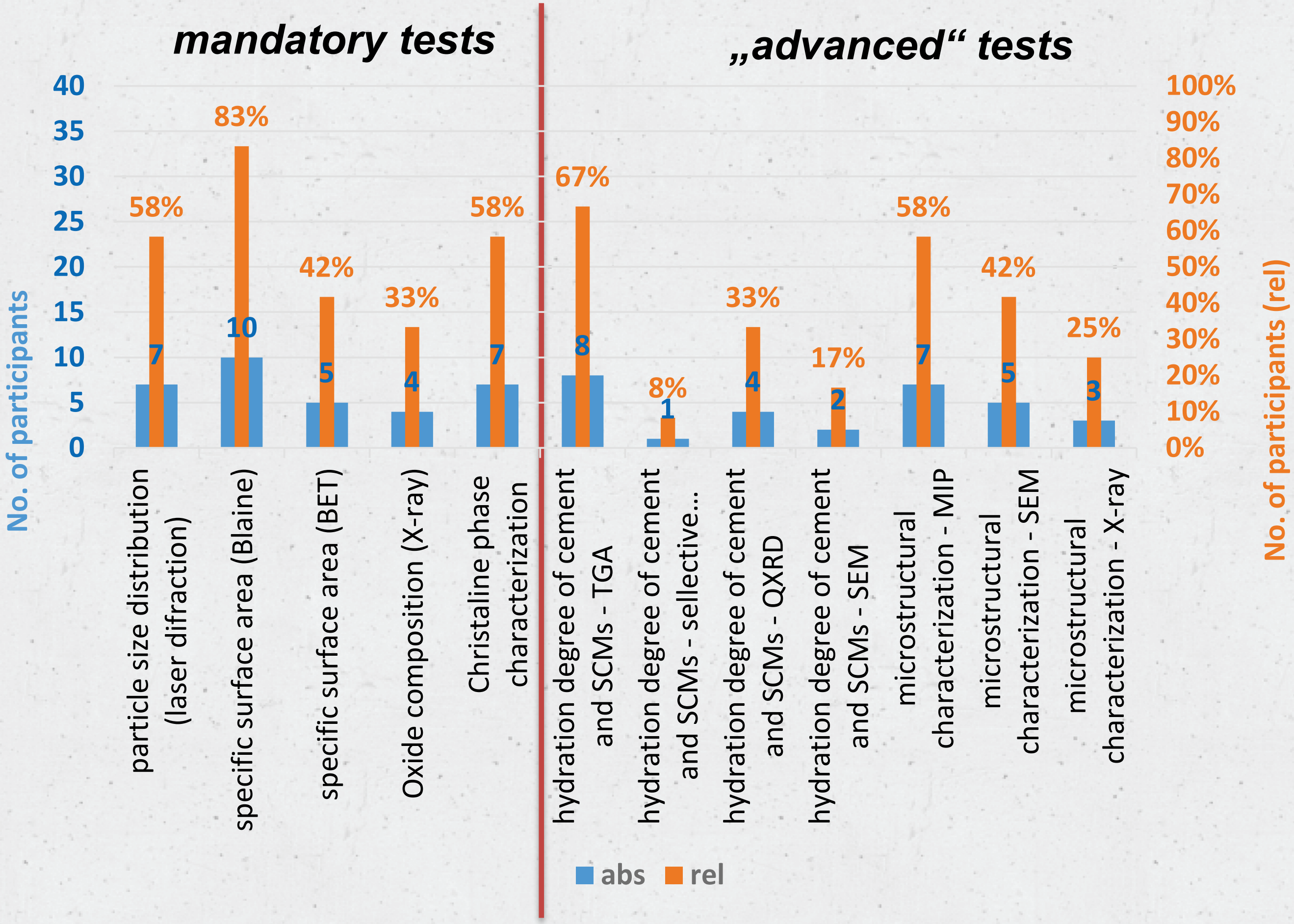
Participants interested in GP1a: Fresh properties and setting



- **No. of interested organizations:** 31
- **% of participants interested in mandatory test:** 45-81%
- **% of participants interested in additional tests:** 19-48%
- **Most interesting „advanced" test:** US technique (15 participants)

SUMMARY (STATISTISTICS) OF RRT+

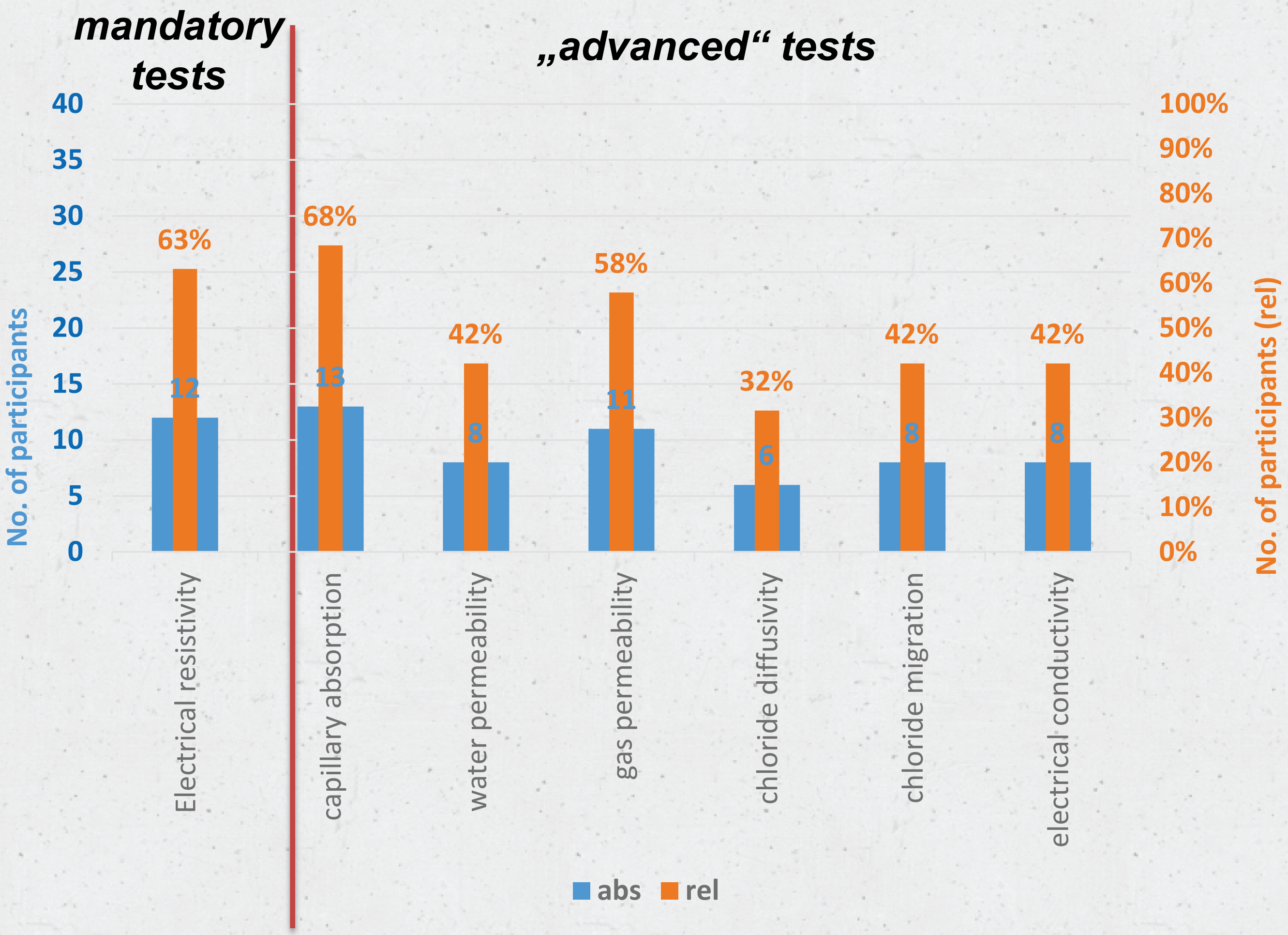
Participants interested in GP1b: Mechanical and micostructural characterization



- **No. of interested organizations:** 12
- **% of participants interested in mandatory test:** 33-83%
- **% of participants interested in additional tests:** 8-67%
- **Most interesting „advanced“ test:** hydration degree of cement using TGA (8 participants)

SUMMARY (STATISTISTICS) OF RRT+

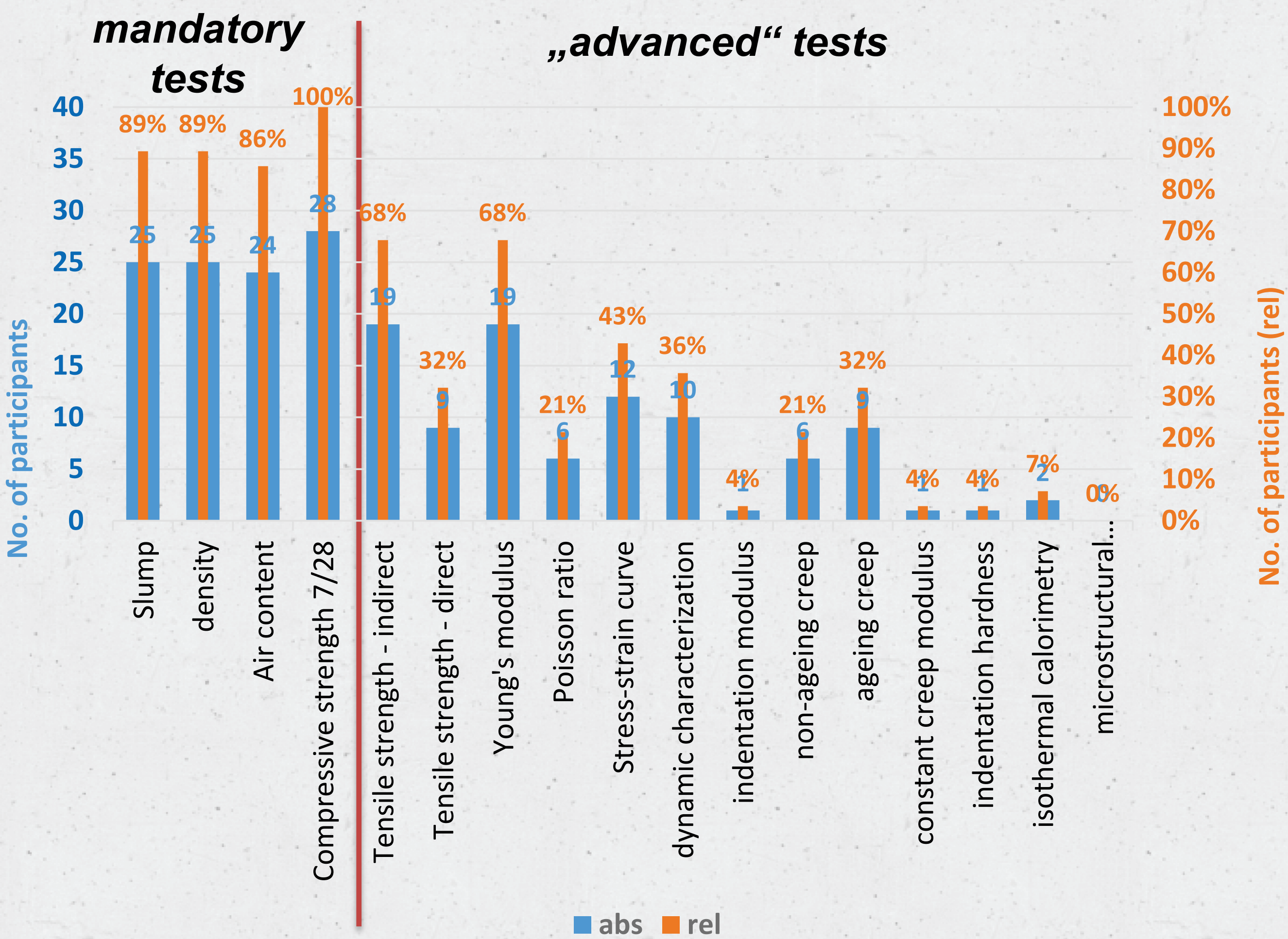
Participants interested in GP1c: Transport properties and boundary effects



- **No. of interested organizations:** 19
- **% of participants interested in mandatory test:** 63%
- **% of participants interested in additional tests:** 32-68%
- **Most interesting „advanced" test:** determination of capillary absorption (13 participants)

SUMMARY (STATISTISTICS) OF RRT+

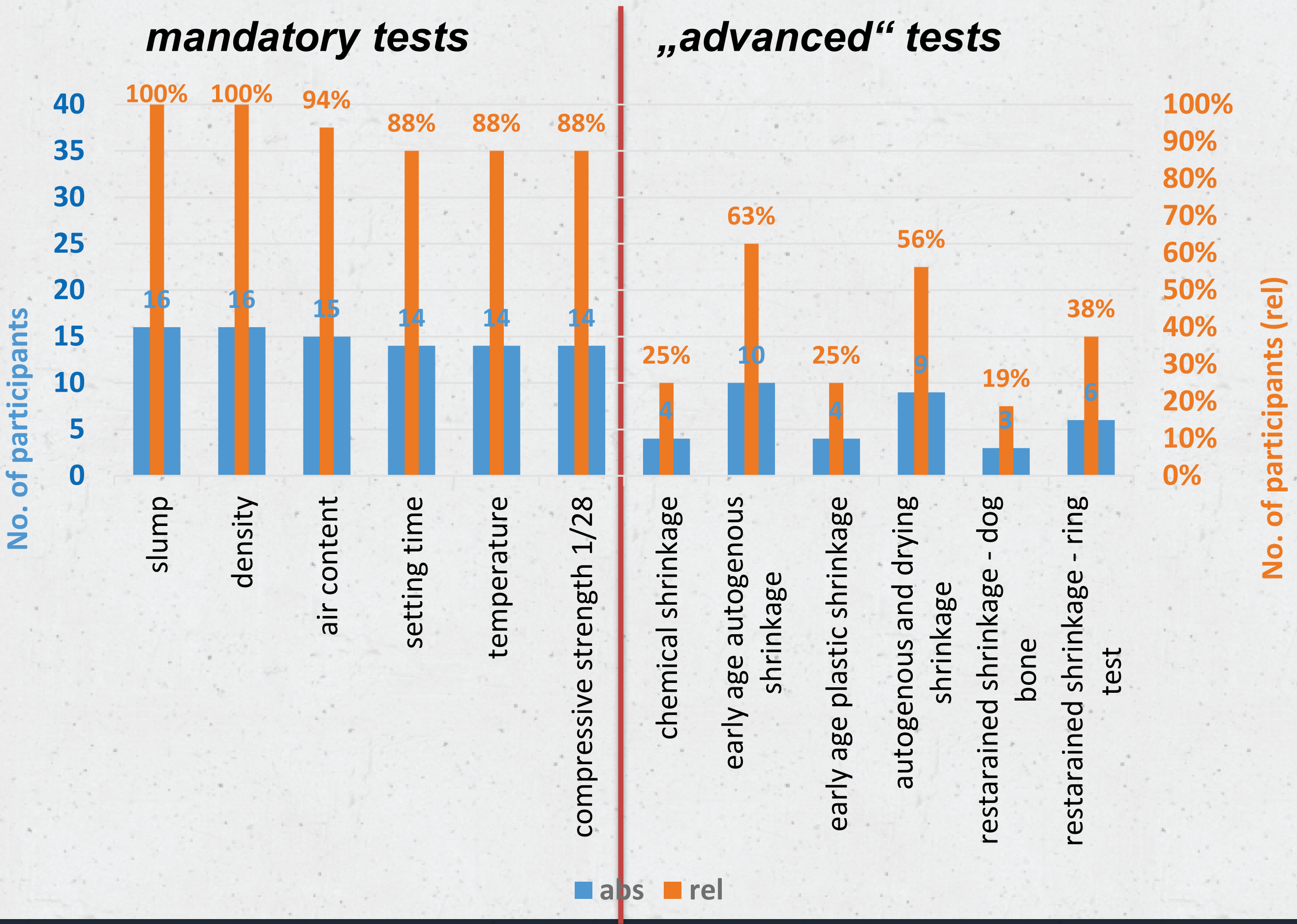
Participants interested in GP1d: Mechanical properties



- **No. of interested organizations:** 28
- **% of participants interested in mandatory test:** 86-100%
- **% of participants interested in additional tests:** 0-68%
- **Most interesting „advanced“ test:** indirect tenile strength, young's modulus (19 participants)

SUMMARY (STATISTISTICS) OF RRT+

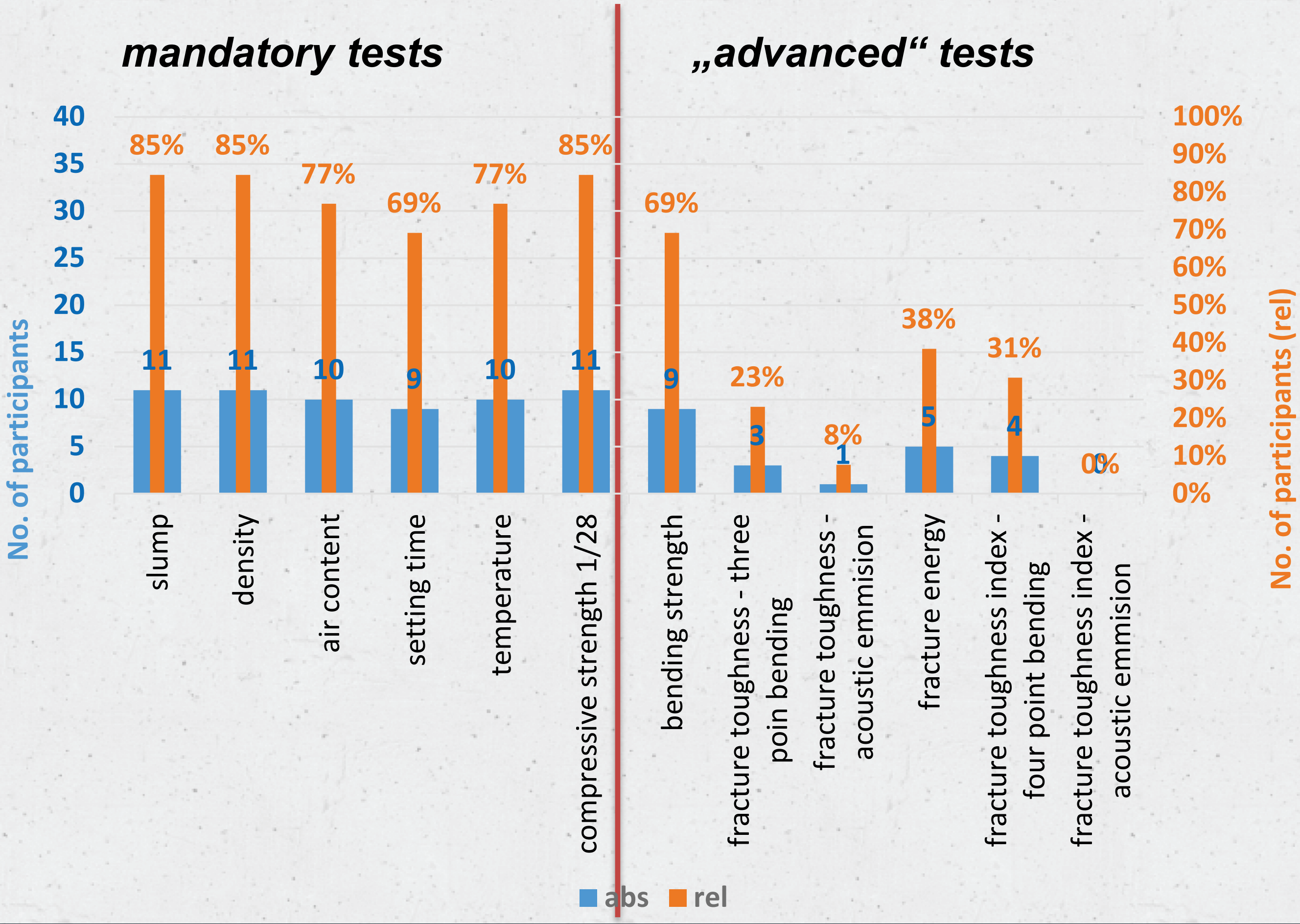
Participants interested in GP1e: Volume stability



- **No. of interested organizations:** 16
- **% of participants interested in mandatory test:** 88-100%
- **% of participants interested in additional tests:** 19-63%
- **Most interesting „advanced“ test:** early age autogenous shrinkage (10 participants)

SUMMARY (STATISTISTICS) OF RRT+

Participants interested in GP1f: Fracture properties and cracking



- **No. of interested organizations:** 13
- **% of participants interested in mandatory test:** 69-85%
- **% of participants interested in additional tests:** 8-69%
- **Most interesting „advanced“ test:** determination of bending strength(9 participants)

ORGANIZATION OF SUBGROUPS

(Participants interested in the same „advanced“ testing techniques)

- **Idea:** to bring together all the participants interested in the same „advanced“ testing techique (DIV 3, type A) and to define experimental materials and mixtures (DIV 2, level 2), curing conditions, timelines, leader of the subgroup, etc.
- **Procedure:** **each interested participants** performs experiments on the **same predefined materials** under the **same predefined curing condition** using **their own experimental technique and procedure.**
- **Results:** **Experimental report** showing all the results, comparison between the results and statistical analysis of the results,
- **Final outcome:** **to recommend universal experimental procedure(s)** and **most appropriate testing technique(s)** with the objective to become **standard** in the near future.

SOME REMARKS…

Managing team of RRT+ procedure would like to thank all the participants for showing great interest in RRT+ and their great contribution needed to achieve all the objectives of the design phase of RRT+ procedure.

We kindly ask you to carefully read the initial RRT+ document entitled „Instructions for participation".

All the participants are kindly ask to perform all the experiments carefully, responsibly, according to valid standards and instructions provided in RRT+ document and to respect deadlines which will be defined shortly.

Based on the number of the participants and amount of experimental materials, our RRT+ can be considered as one of the largest round robin testing programs in Europe.

TU 1404
COST ACTION

[Back to the list of presentations](#)

Vienna, September 20, 2015

TU 1404 COST ACTION

TOWARDS THE NEXT GENERATION OF STANDARDS FOR SERVICE LIFE OF CEMENT-BASED MATERIALS AND STRUCTURES

Status of the Round Robin Test RRT +

on different properties of cement based materials

DESIGN and INITIAL PHASES

Stéphanie Staquet, sstaquet@ulb.ac.be

Dirk Schlicke, dirk.schlicke@tugraz.at

Emmanuel Rozière, Emmanuel.Roziere@ec-nantes.fr

Gregor Trtnik, Marijana Serdar, Miguel Azenha

ESF provides the COST Office through a European Commission contract

COST is supported by the EU Framework Programme

COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

RRT+ ORGANIZATION

- DIVISION OF RRT+
  - **DIV 1: DIFFERENT PHASES OF RRT**
    - DESIGN PHASE
    - EXPERIMENTAL PHASE
      - INITIAL PHASE
      - MAIN PHASE
      - ADDITIONAL PHASE
  - **DIV 2: DIFFERENT EXPERIMENTAL MATERIALS**
    - LEVEL 0: Reference mixtures (OC, MOC, OM, OCP)
    - LEVEL 1: sustainable and innovative mixtures
    - LEVEL 2: changes in basic materials
  - **DIV 3: DIFFERENT INTEREST OF PARTICIPANTS**
    - TYPE A PARTICIPANTS: interested mainly in novel techniques
    - TYPE B PARTICIPANTS: Interested mainly in developing sustainable mixtures

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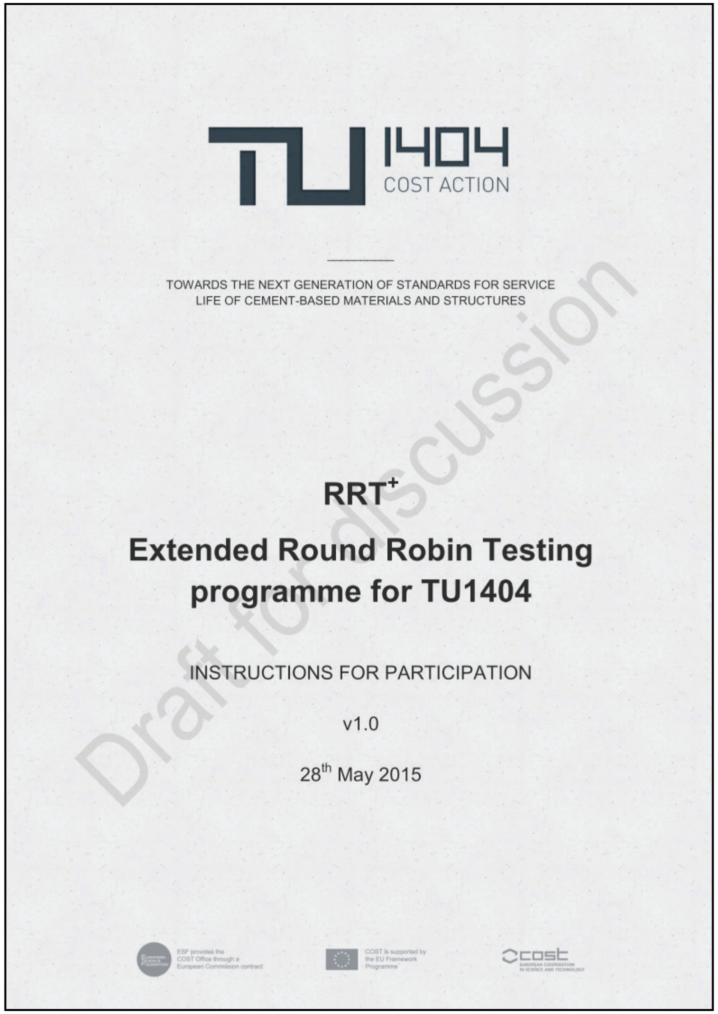
STATUS OF RRT+



TU 1404 COST ACTION

TOWARDS THE NEXT GENERATION OF STANDARDS FOR SERVICE LIFE OF CEMENT-BASED MATERIALS AND STRUCTURES

Draft for discussion

RRT+

Extended Round Robin Testing programme for TU1404

INSTRUCTIONS FOR PARTICIPATION

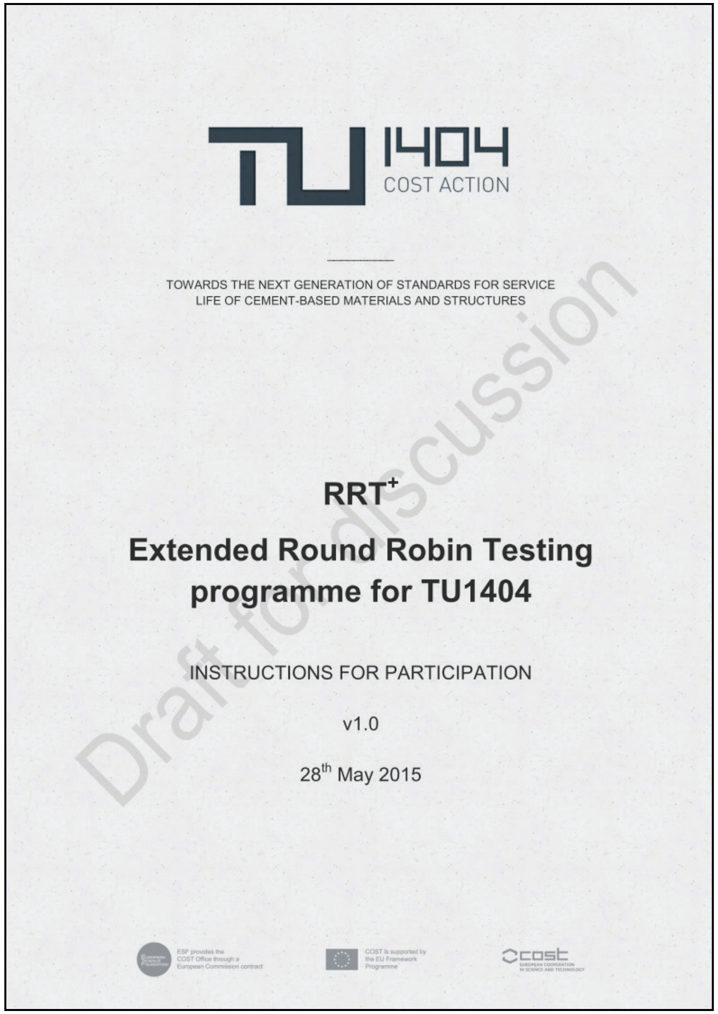
v1.0

28th May 2015

The first RRT+ document entitled „*Instruction for participation*“:

- Section 1: Introduction (general facts of COST TU1404 Action and RRT+ procedure)
- Section 2: description and instructions for participation in initial experimental phase
- Section 3: description and instructions for participation in main experimental phase:

STATUS OF RRT+



TU 1404 COST ACTION

TOWARDS THE NEXT GENERATION OF STANDARDS FOR SERVICE LIFE OF CEMENT-BASED MATERIALS AND STRUCTURES

RRT+

Extended Round Robin Testing programme for TU1404

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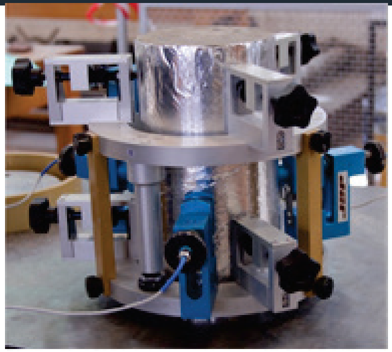
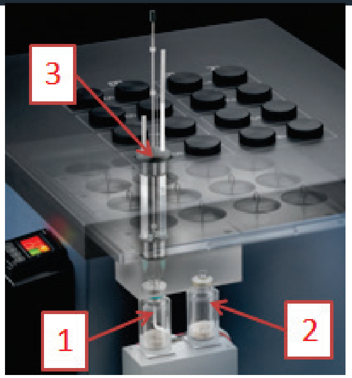
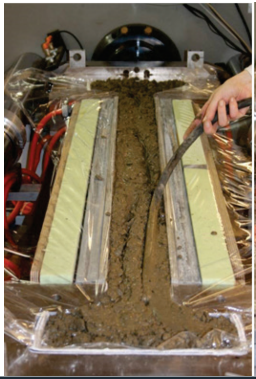
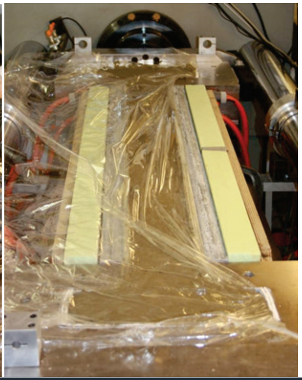
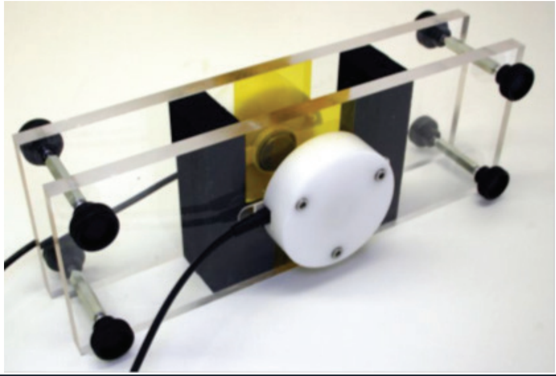
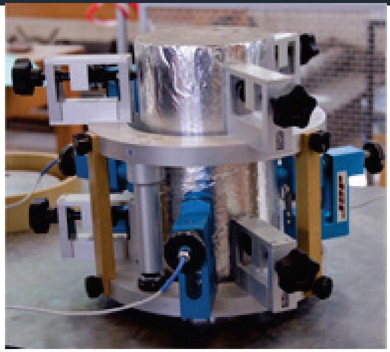


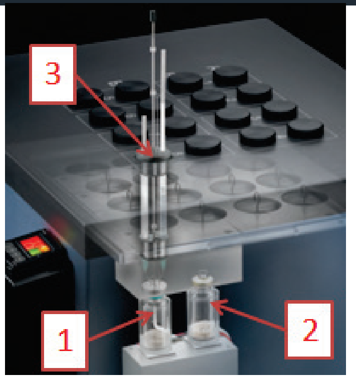


RRT+ ?

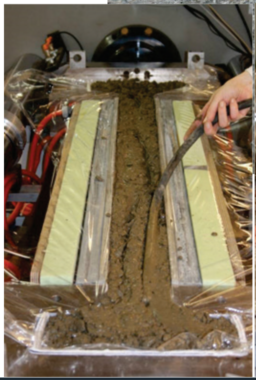


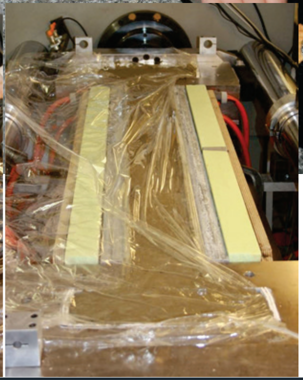




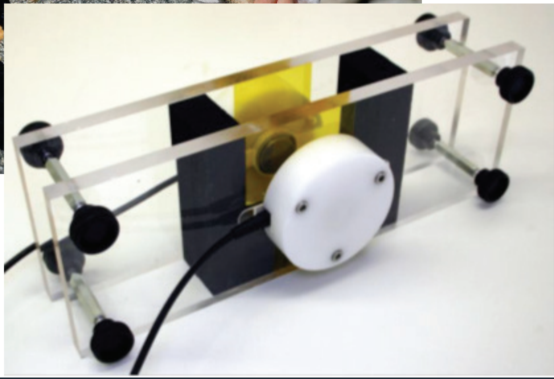





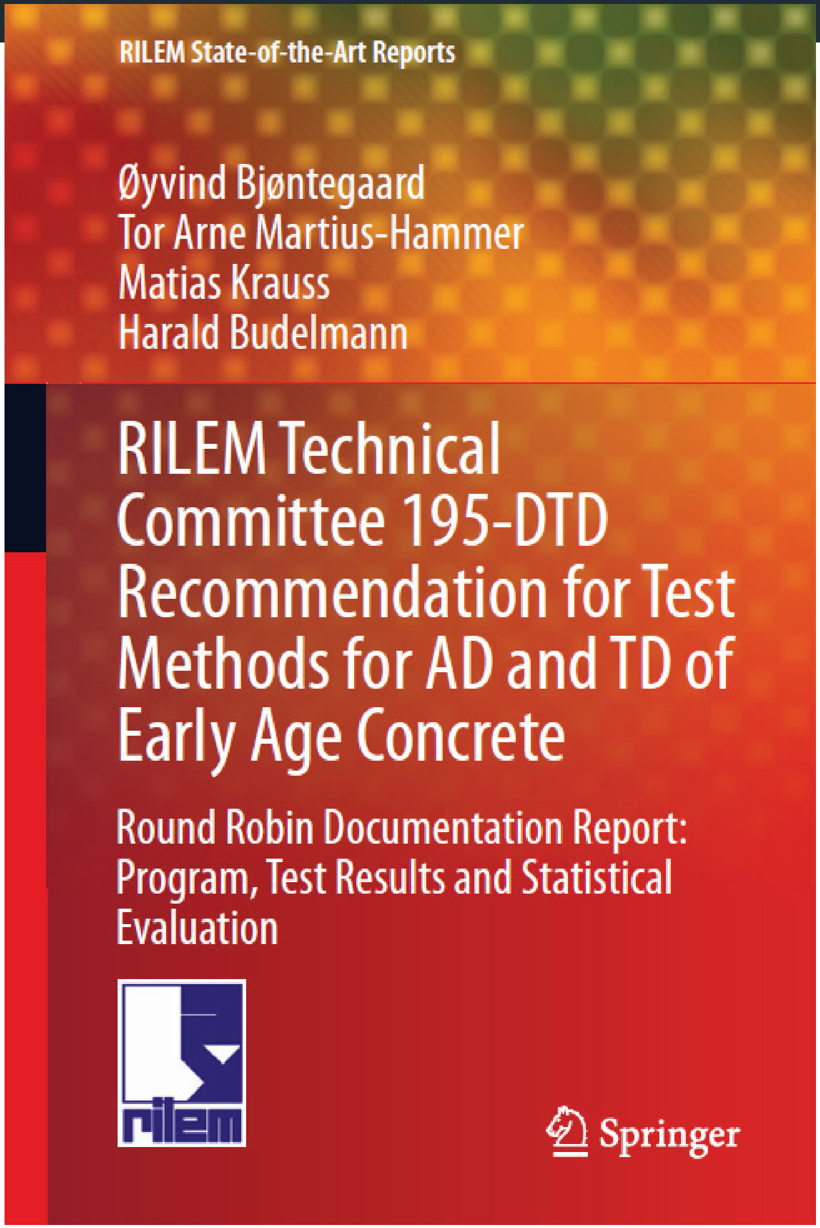
How to manage ?







Lessons learnt from →



1. Final report with the Round Robin test results

2. Bjøntegaard Ø. and Hammer T.A. (2006) RILEM Technical Committee 195-DTD: Motive and technical content.

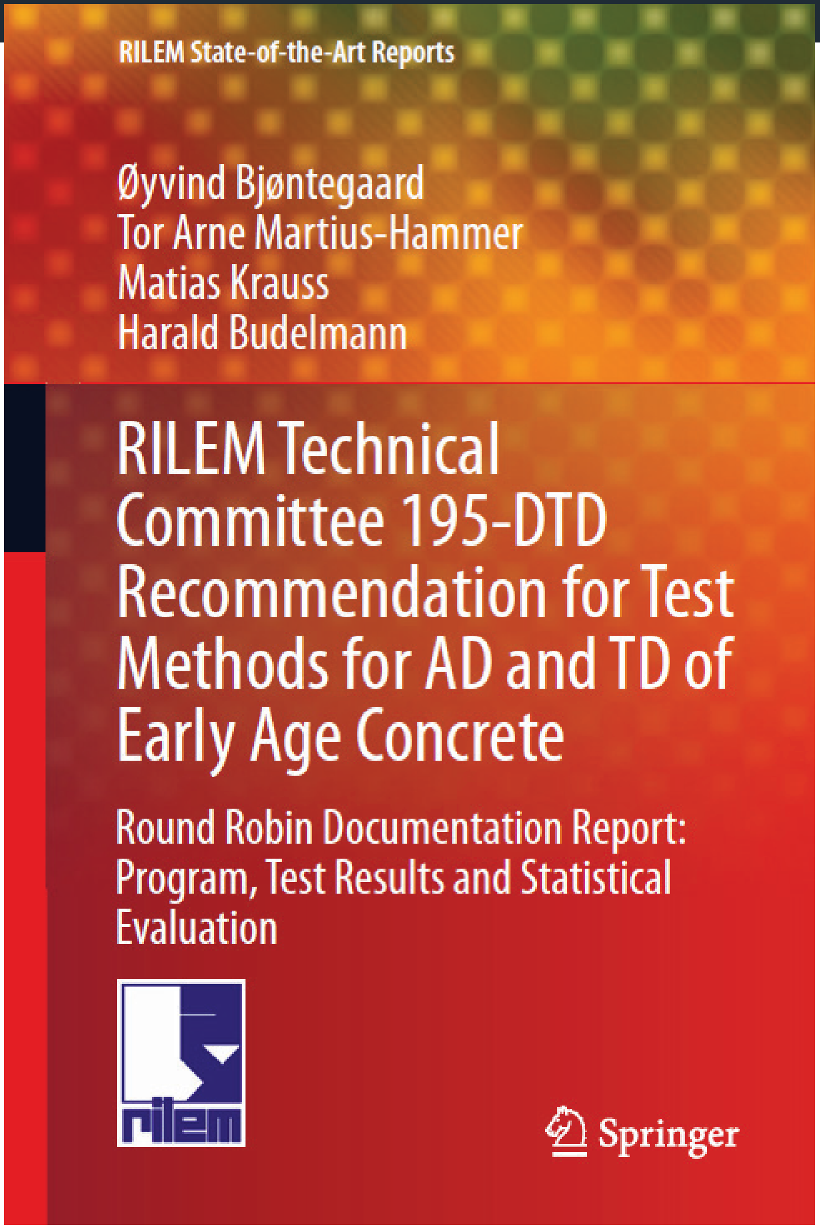
3. Krauss. M., Bjøntegaard Ø. and Hammer T.A. (2006) Statistical evaluation of autogenous deformation test results performed in the RILEM Technical Committee 195-DTD framework.

4. Hammer T.A. and Bjøntegaard Ø. (2006) Testing of autogenous deformation (AD) and thermal dilation (TD) of early age mortar and concrete – recommended test procedure.

Ref 2-4: In Proc. of the Int. RILEM conference on Volume Changes of Hardening Concrete: Testing and Mitigation, 20-23 Aug. 2006, Tech. Univ. of Denmark, Lyngby, Denmark

Main sources of variations

1. Preparation of the materials: wrong water/binder ratio (**initial aggregate moisture state**), wrong aggregate size.
2. Initial **air content**
3. Initial temperature of fresh concrete, malfunction of **temperature control**.
4. **Amount of superplasticizer**.
5. Excessive **bleeding**.



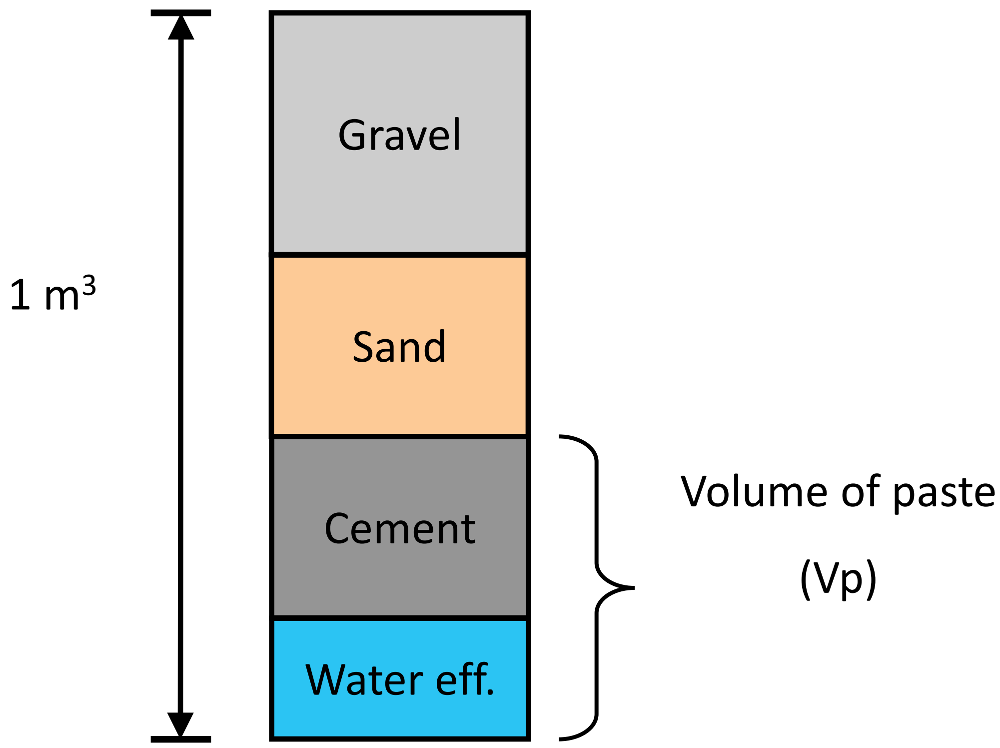
1. Preparation of the materials

Preparation of aggregates and concrete mixtures

Influence of mix-design parameters

Vercors concrete

$W_{eff}/C = 0.52$



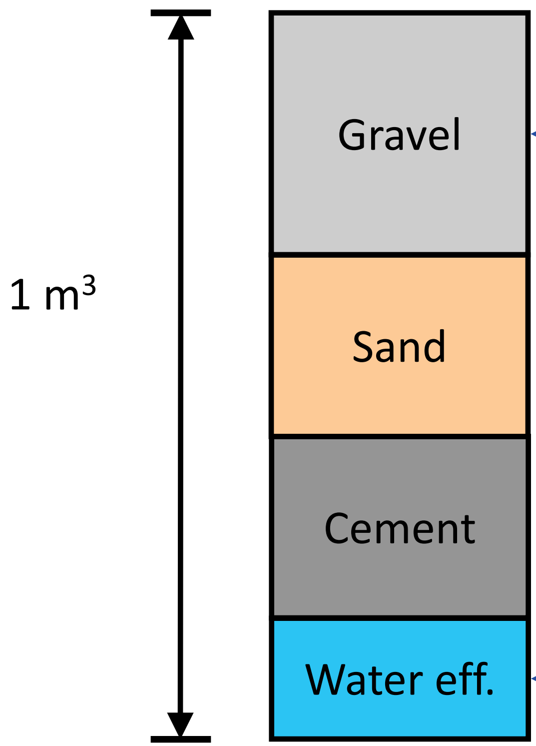
Ordinary concrete (OC)

Preparation of aggregates and concrete mixtures

Influence of mix-design parameters

Vercors concrete

$W_{eff}/C = 0.52$



Ordinary concrete (OC)

Effective water

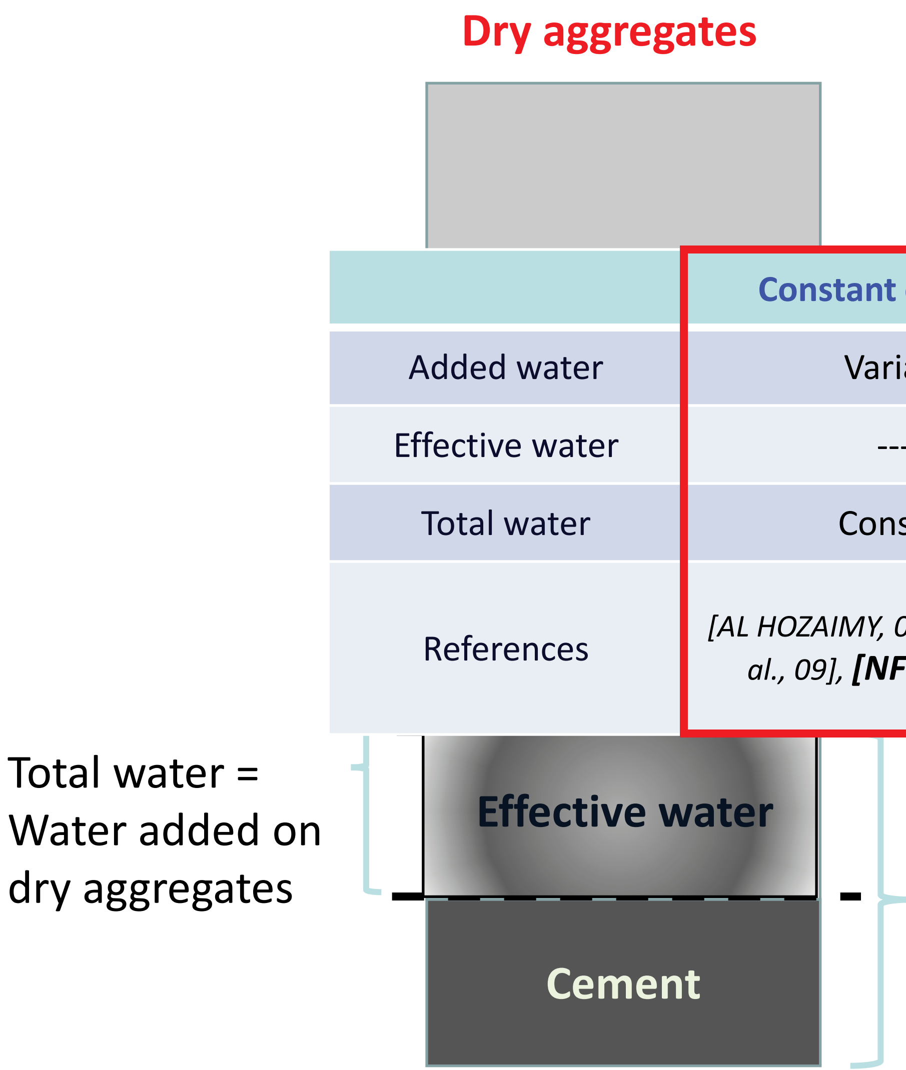
$$W_{eff} = W_{added / dry\ aggregates} - W_{absorbed}$$

	Absorption coefficient (% of dry mass)
Gravel 2	**2.25**
Gravel 1	**2.61**
Sand	0.77

Preparation of aggregates and concrete mixtures

Influence of mix-design parameters

	Constant eff. water	Constant add. water
Added water	Variable	-----
Effective water	-----	Variable
Total water	Constant	Variable
References	*[AL HOZAIMY, 09], [PEREIRA et al., 09],* ***[NF EN 206-1]***	*[TOMA, 99], [KHOON Ng & CHI Ng, 11]*

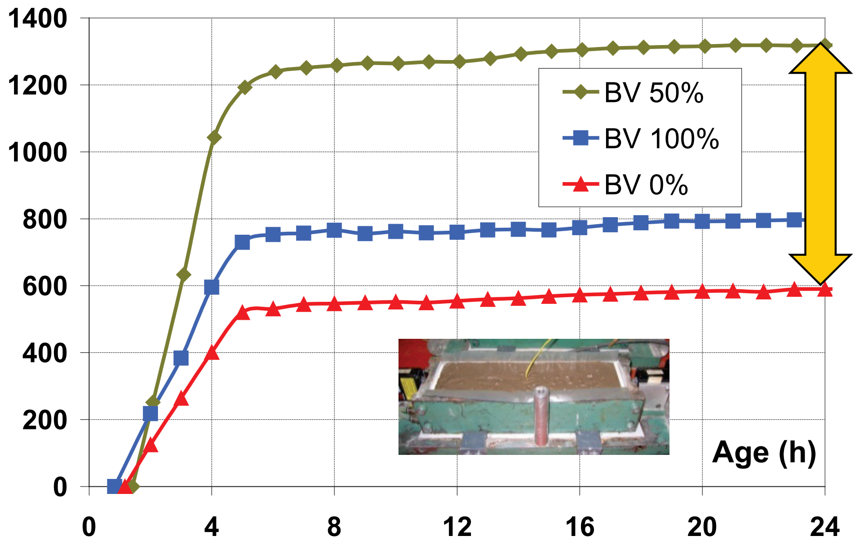


$$W_{Eff} = W_{Added / Dry\ aggregates} - W_{Absorbed}$$

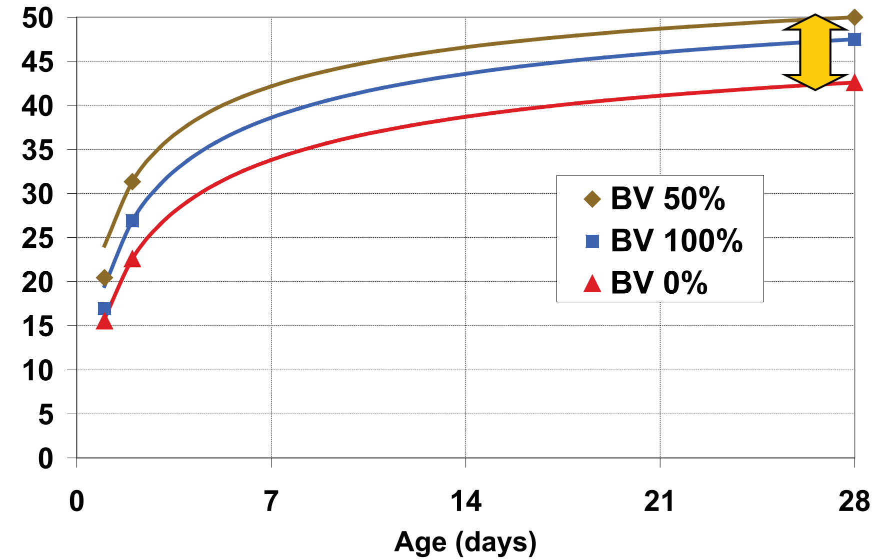
Preparation of aggregates and concrete mixtures

Influence of mix-design parameters: initial water saturation

Plastic shrinkage



Compressive strength

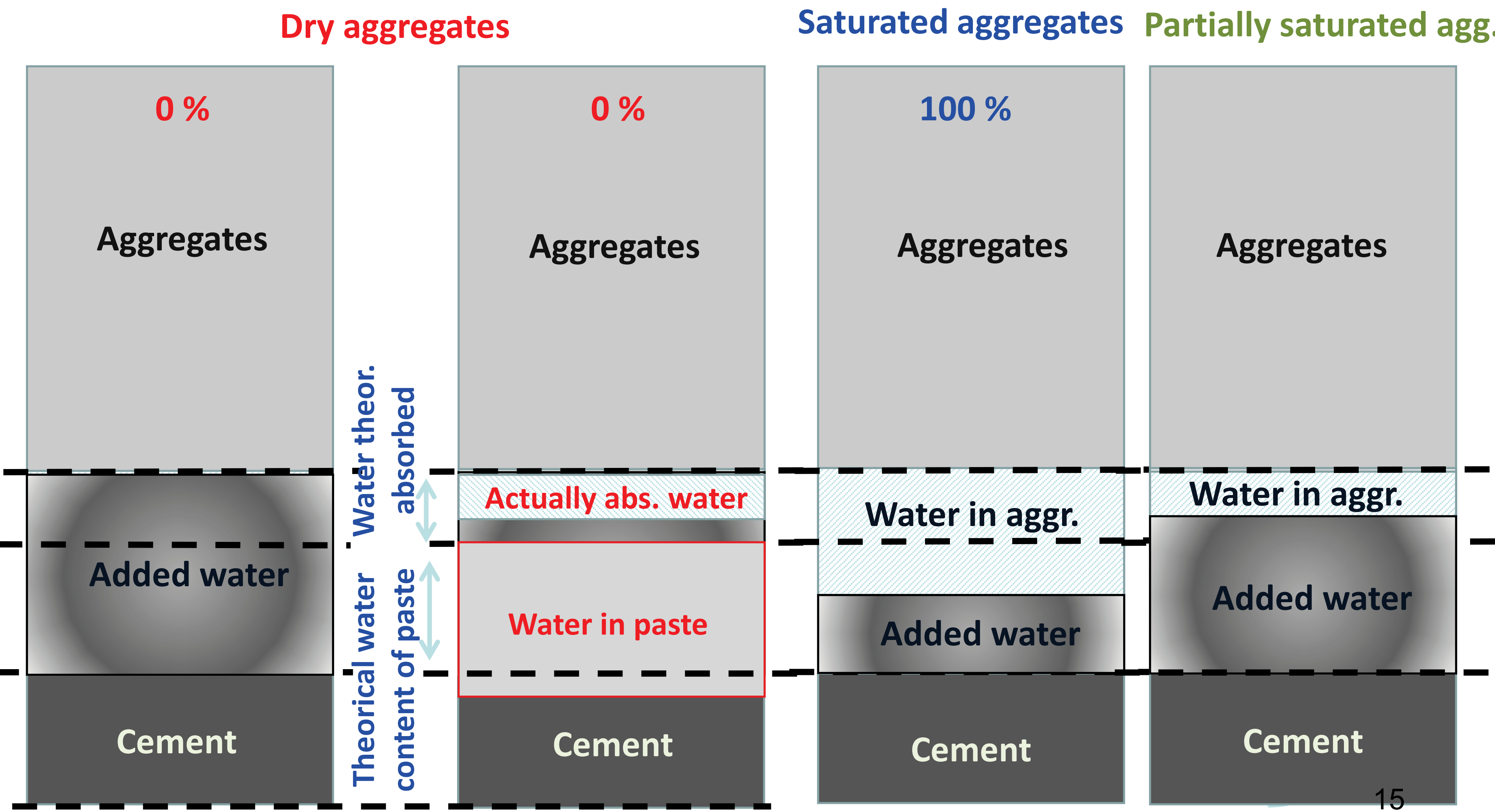


⇒ Significant Influence of initial water saturation of aggregates on shrinkage and mechanical properties of concrete [*Cortas et al., CCC, 2014*]

⇒ If dry aggregates are used, water actually absorbed < water theoretically absorbed, thus higher (unknown) Water eff./Cement ratio

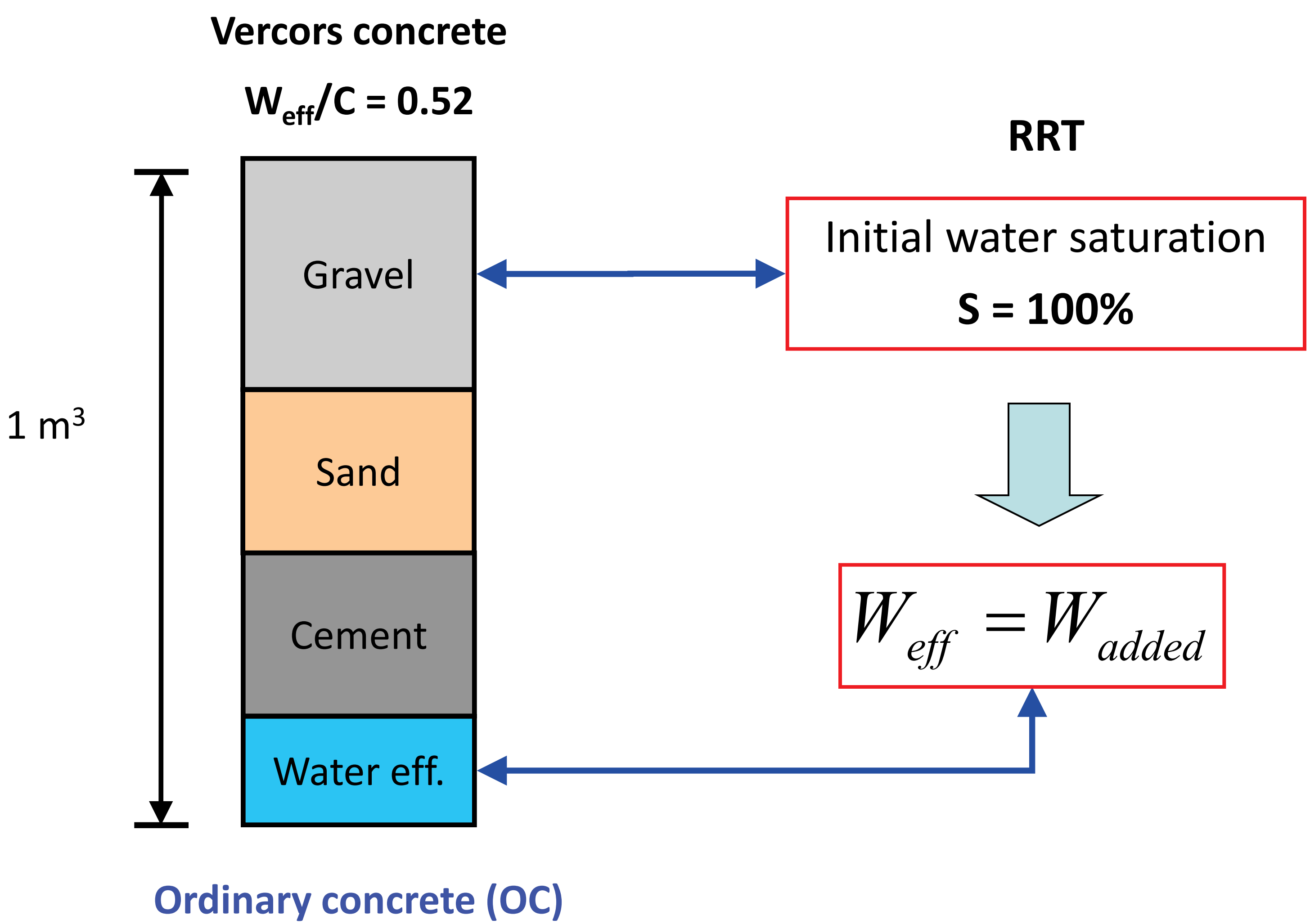
Preparation of aggregates and concrete mixtures

Influence of mix-design parameters: initial water saturation



Round Robin Test (RRT) programme

Influence of mix-design parameters: initial water saturation



Round Robin Test (RRT) programme

Preparation of aggregates

1

Materials kept under controlled laboratory conditions
ambient temperature TA = 20 ± 2°C,
relative humidity RH ≥ 60

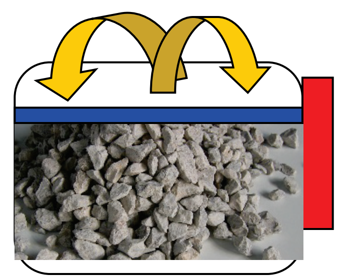
2

Measurement of initial water content :
W = Wini %
(% of dry mass)

3

Add water corresponding to the difference between the initial water content & the absorption coefficient:
WA24 - Wini

4

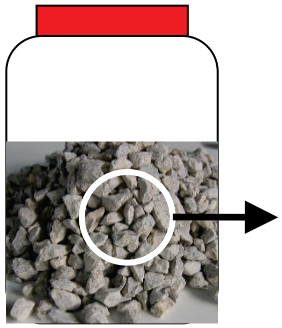


Mix the aggregates and added water

Round Robin Test (RRT) programme

Preparation of aggregates and sand

5



Take 3 samples and measure the final water content :
W = W0 %
(% of dry mass)

6

Write the initial W0% in the .xls file

	Absorption coef. (% of dry mass)	Water content (% of dry mass)
Gravel 2	2.25	2.24
Gravel 1	2.61	2.5
Sand	0.77	0.8

Round Robin Test (RRT) programme

Trial tests in the lab at ULB on the Vercors OC, Brussels in July 2015

Round Robin Test (RRT) programme

Trial tests at ULB, Brussels in July 2015

	INITIAL STATE OF SATURATION					
	Total weight before drying	Total weight AFTER drying	Water content	Water content (%)	Average % of water	Absorption coef.
	420,588	417,705	0,012	1,178	1,060	
	423,637	420,453	0,013	1,280		
Gravel 2	403,768	402,113	0,007	0,723		2,25
	378,892	376,976	0,009	0,932	0,992	
	385,177	383,090	0,010	0,999		
Gravel 1	393,293	391,050	0,010	1,045		2,61
	281,589	279,513	0,019	1,921	2,356	
	273,489	271,191	0,023	2,313		
Sand	275,660	272,815	0,028	2,833		0,77

Round Robin Test (RRT) programme

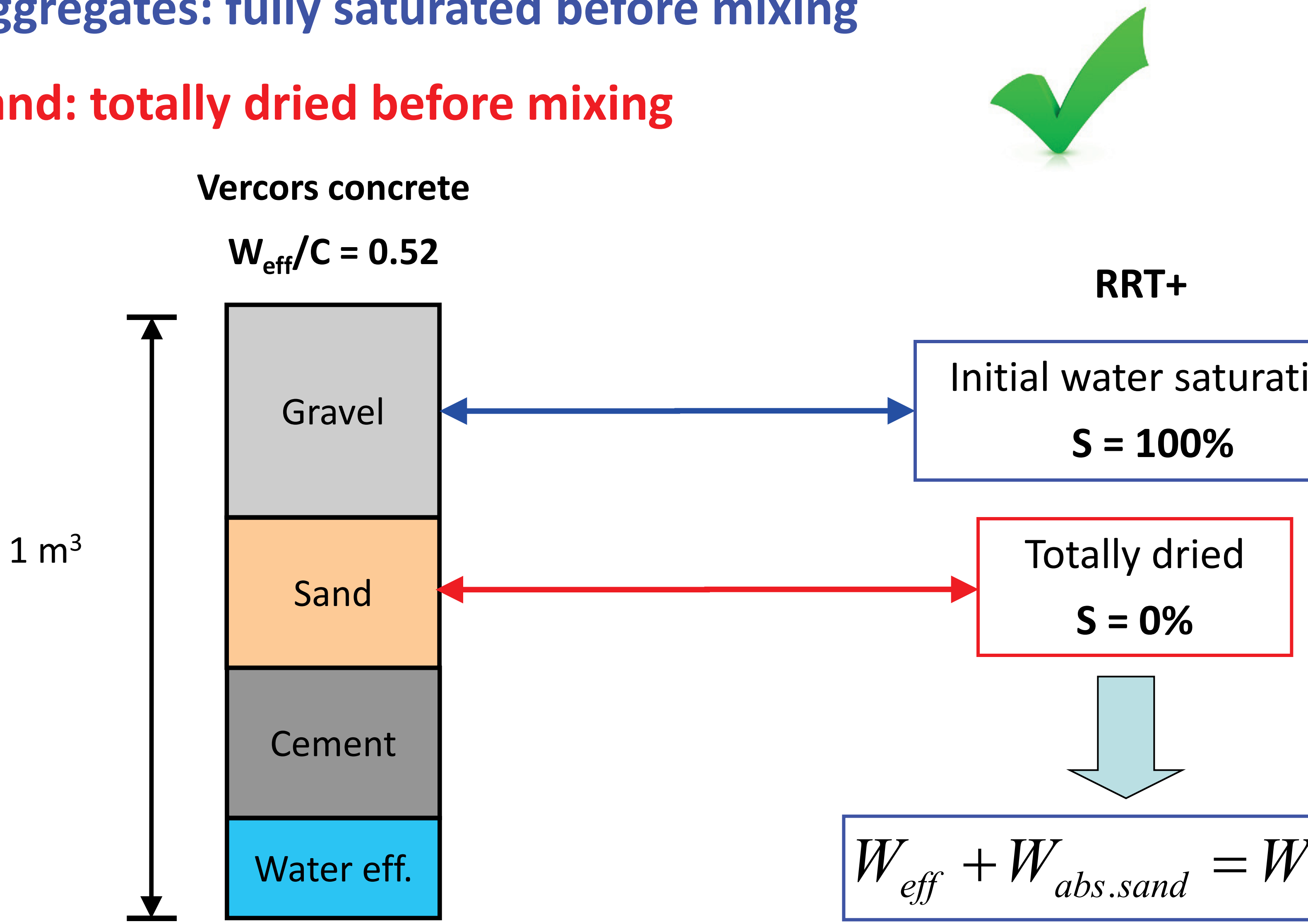
Trial tests at ULB, Brussels in July 2015

	INITIAL STATE OF SATURATION					
	Total weight before drying	Total weight AFTER drying	Water content	Water content (%)	Average % of water	Absorption coef.
Gravel 2	420,588	417,705	0,012	1,178	1,060	2,25
	423,637	420,453	0,013	1,280		
	403,768	402,113	0,007	0,723		
Gravel 1	378,892	376,976	0,009	0,932	0,992	2,61
	385,177	383,090	0,010	0,999		
	393,293	391,050	0,010	1,045		
Sand	281,589	279,513	0,019	1,921	2,356	0,77
	273,489	271,191	0,023	2,313		
	275,660	272,815	0,028	2,833		

Round Robin Test (RRT+) programme

Aggregates: fully saturated before mixing

Sand: totally dried before mixing



$$W_{eff} + W_{abs.sand} = W_{added}$$

Ordinary concrete (OC)

2. Modified mixtures : concrete – mortar – paste for multi-scale modelling

RRT+

2. Modified mixtures : concrete – mortar – paste for multi-scale modelling

RRT+

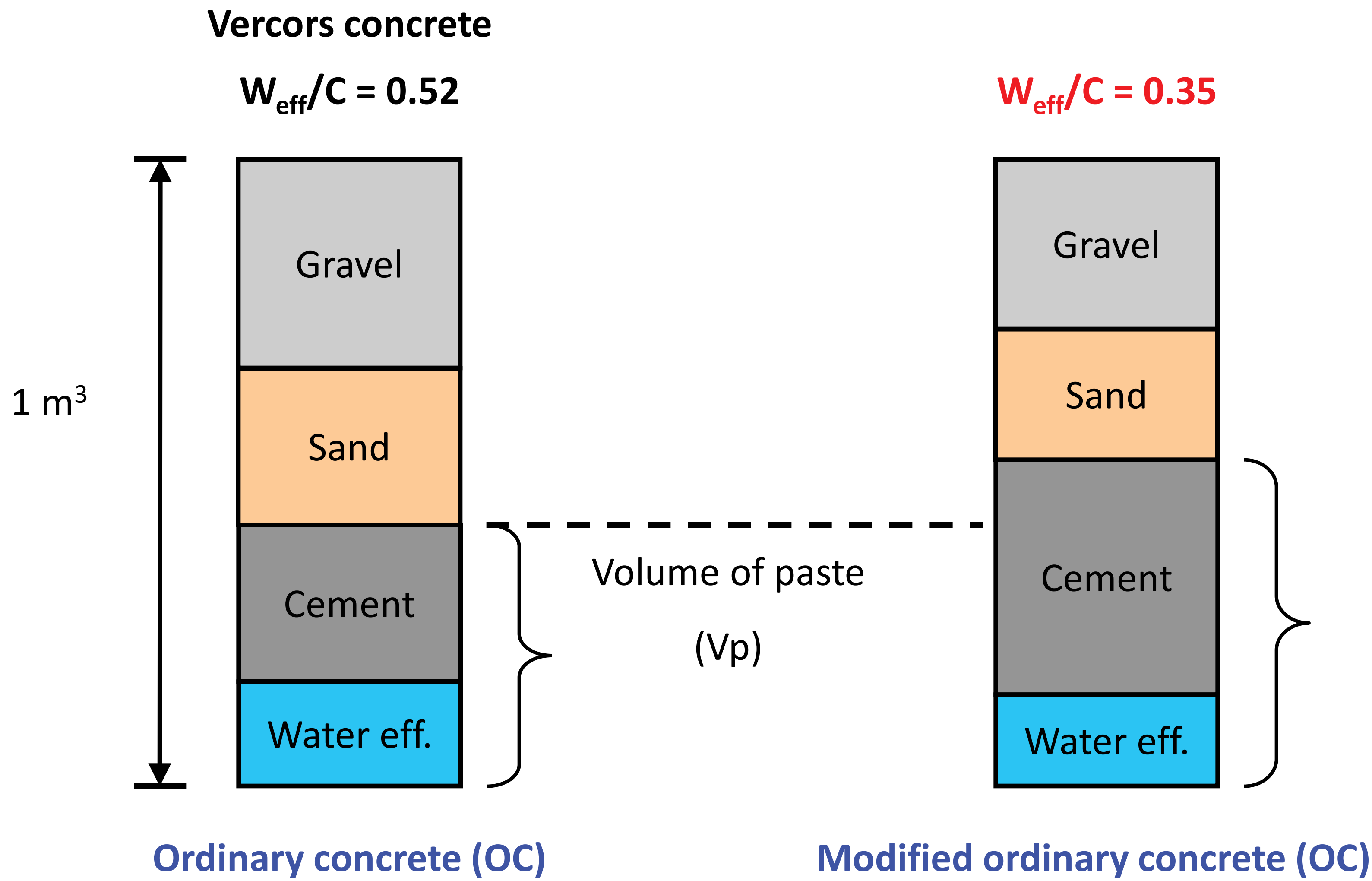
Trial tests in concrete laboratory

in ECNantes

in June 2015

Preparation of aggregates and concrete mixtures

Influence of mix-design parameters



Modified concrete

Cement, C	451
Weff/C	0.35
Volume of paste (Vp), l/m3	320

Vercors HPC

Friday 20 March 2015

Vercors		Vt	1000		
Initial concrete mixture		Vp	320		
		Vg	680	Batch	
	MV (kg/l)	M (kg/m3)	V (l)	40	L
Gravel 2 : 8/16 R Balloy	2.58	526	203.9		
		538		21.52	kg
Gravel 1 : 4/11 R GSM LGP1	2.53	426	168.3		
		436		17.46	kg
Sand 0/4 REC GSM LGP1	2.58	794	307.8		
		800		32.02	kg
Cement CEM I 52,5 N CE CP2 NF G	3.17	451	142.2	18.03	kg
Sp (SIKAPLAST techno 80)	1.06	5.0	5.30	0.200	kg
Water added	1	154.1	152.0	6.163	kg
Water total	1	186.9	186.9		
Water absorbed	1	29.1	29.1		
Water superplasticizer	1	4.0	4.0		
Water effective	1	157.8	157.8		
	Total	2356	980.0		
		Density	2.404		
		Air (l/m3)	20.0		
	G/S	1.20			
	VG/VS	1.21			
	Sp/C (%)	1.11			

Water added in the mixer

	Absorption coef (% of dry mass)	Water content (% of dry mass)
Gravel 2	2.25	2.24
Gravel 1	2.61	2.5
Sand	0.77	0.8

Time when adding water :		10:00	
Superplasticizer added: (gramme)		62	80
Slump: (mm)		120	180
Targeted consistency is S4 (slump between 160 and 210 mm)			
Temperature fresh concrete: (°C)		19.4	
Air content fresh concrete: (%)		2.5	
Mixing room	Temperature (°C)	18.2	
	RH (%)	64	
Time when starting tests (data logging)	Test 1 :	10:34	
	Test 2 :	10:53	

Vercors initial (NSC) OC | Vercors HPC MOC | Mortar OM | Paste OCP

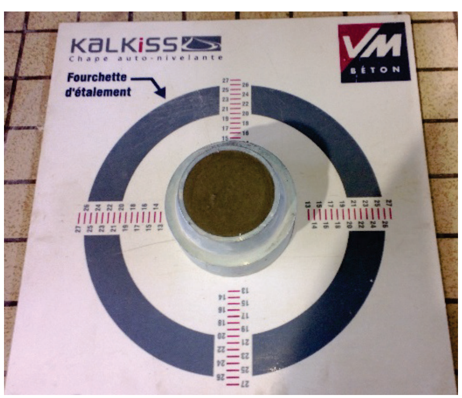
Modified mixtures

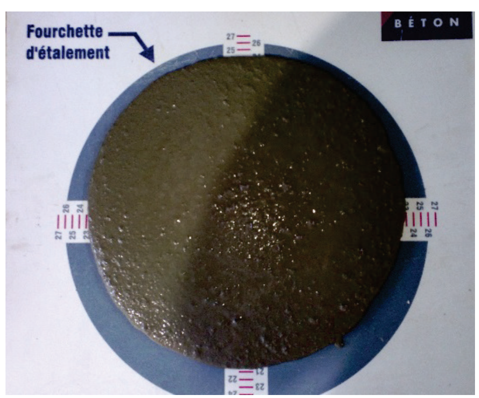
	OC	MOC 1	MOC 2
Cement CEM I 52,5 N CE CP2 NF Gaurain	320	451	496
Sand 0/4 REC GSM LGP1	830	794	759
Gravel 1 : 4/11 R GSM LGP1	445	526	407
Gravel 2 : 8/16 R Balloy	550	426	503
Sp (SIKAPLAST techno 80)	2.4	10.4	7.5
Eau	164.5	149.5	167.6
Weff/C*	0.52	0.35	0.35
Sp/C (%)	0.75	2.31	1.51
Slump (mm)	207	192	190

Modified mixtures

	OM	MOM 1	MOM 2
Cement CEM I 52,5 N CE CP2 NF Gaurain	524	718	770
Sand 0/4 REC GSM LGP1	1359	1265	1178
Sp (SIKAPLAST techno 80)	3.9	16.6	11.6
Water	269.3	238.0	260.2
Weff/C	0.52	0.35	0.35
Sp/C (%)	0.75	2.31	1.51
Slump flow (mm)	230		
Slump - heigth of 150 mm (mm)		43	57

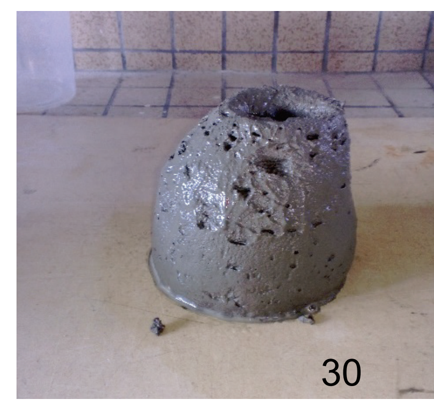
OM





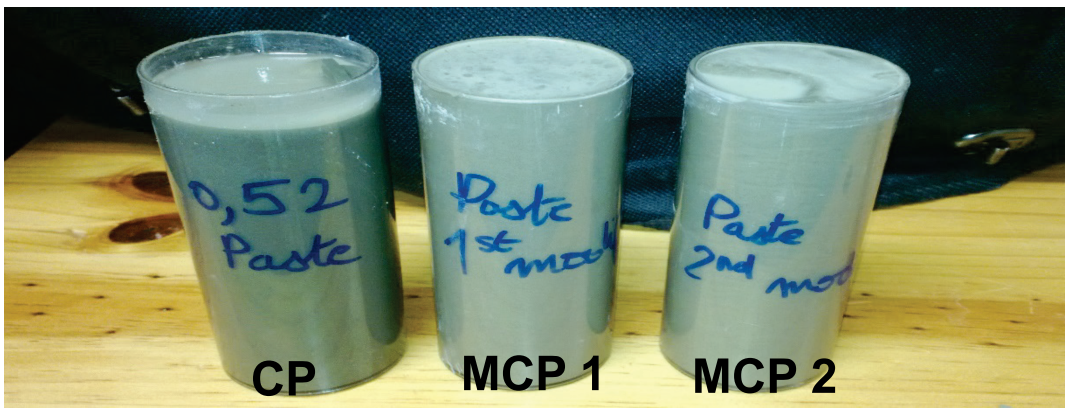
MOM 1

MOM 2



Modified mixtures

	CP	MCP 1	MCP 2
Cement CEM I 52,5 N CE CP2 NF Gaurain	1106	1409	1417
Sp (SIKAPLAST techno 80)	8.3	32.5	21.4
Water	568.5	467.1	478.8
Weff/C	0.52	0.35	0.35
Sp/C (%)	0.75	2.31	1.51
Bleeding (mm)	8	2	1

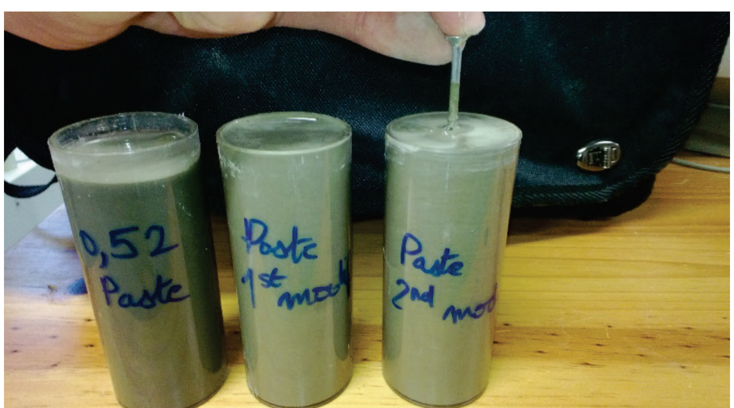


Very good fluidity for each cement pastes

Modified mixtures

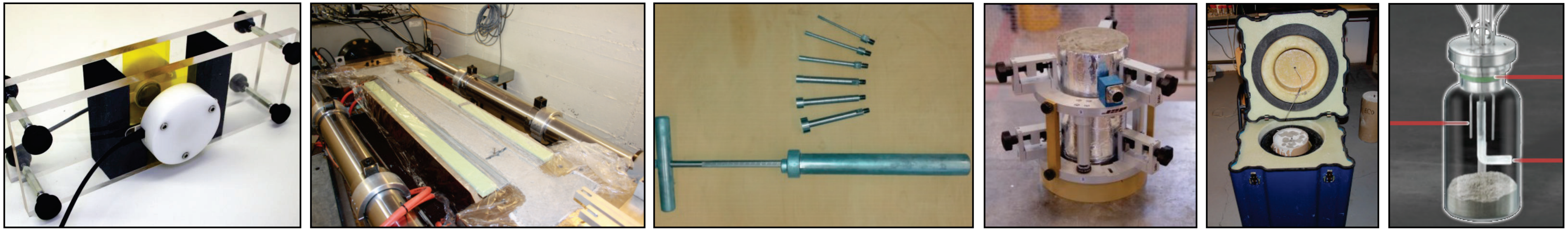
Penetration test. 44 hours after mixing, for ordinary cement paste OCP

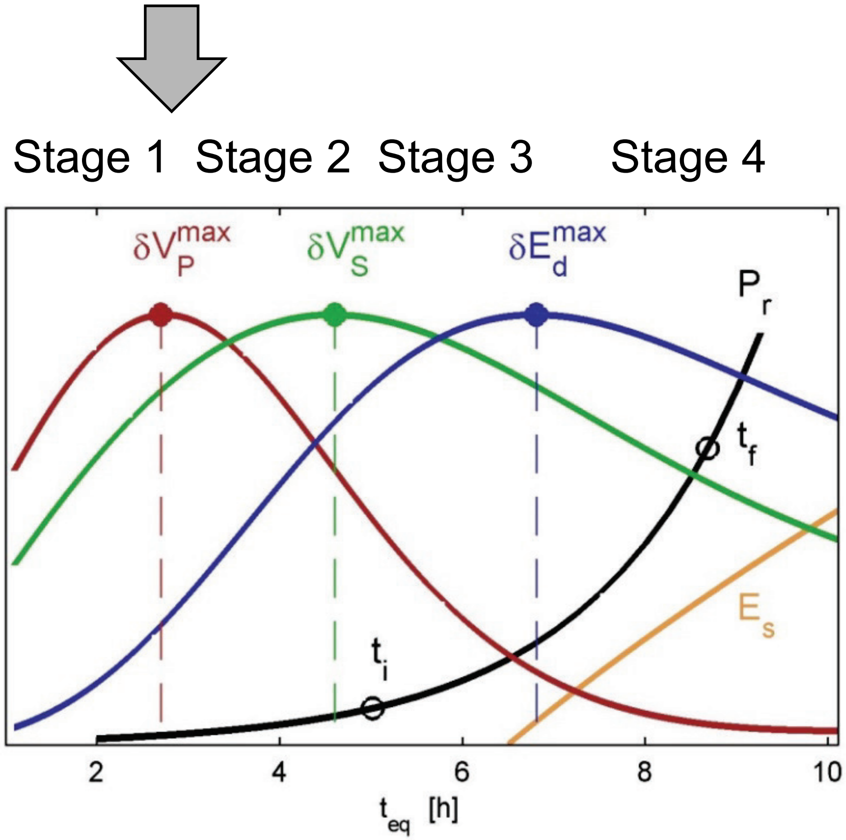
Penetration test. 16 hours after mixing, for modified cement paste MCP1.



Penetration test. 16 hours after mixing, for modified cement paste MCP2.

Modified mixtures – determination of setting at ULB





Stage 1 : dormant period

HYDRATION START (V_P)

Stage 2 : start of solid percolation

INITIAL SETTING (V_S)

Stage 3 : Stiffness increase

FINAL SETTING (E_d)

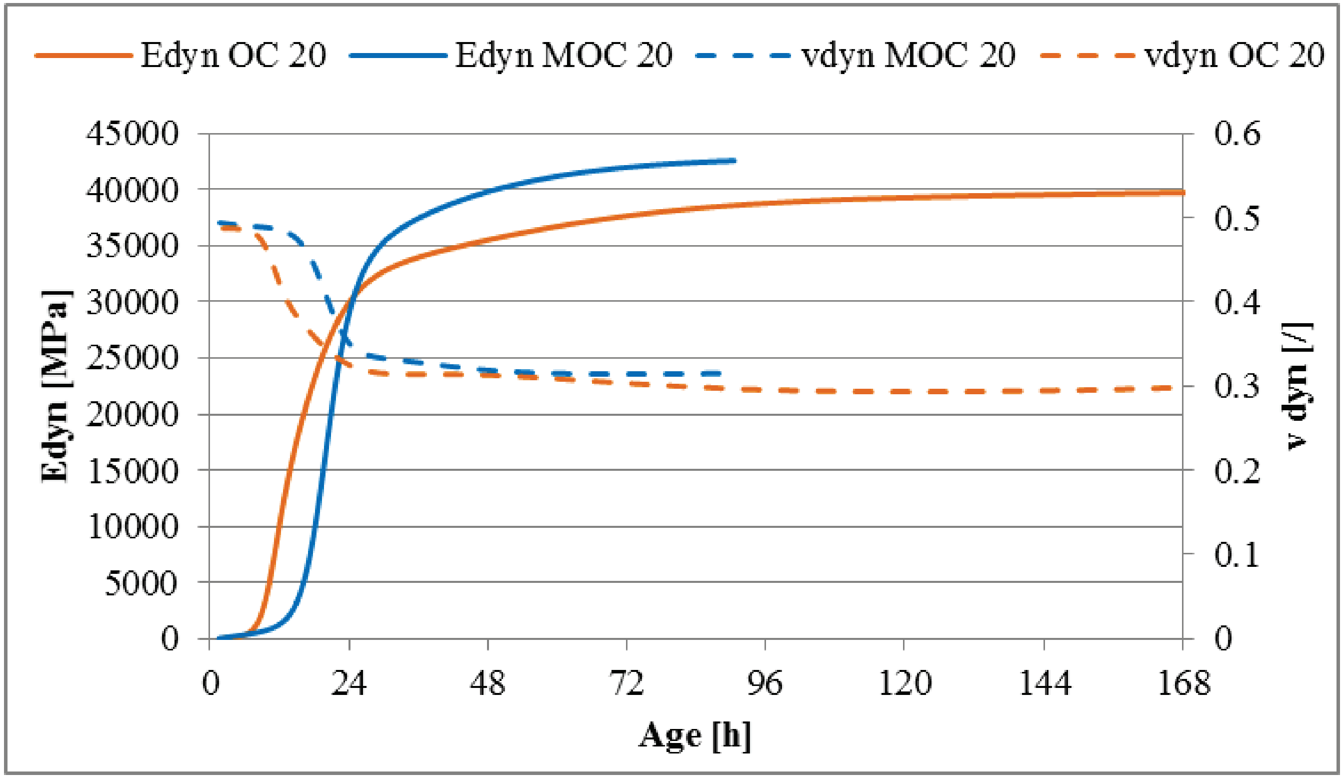
Stage 4 : Stiffness increase with decreasing rate

Initial setting t_i : δV_S^{max}

Final setting t_f : δE_d^{max}

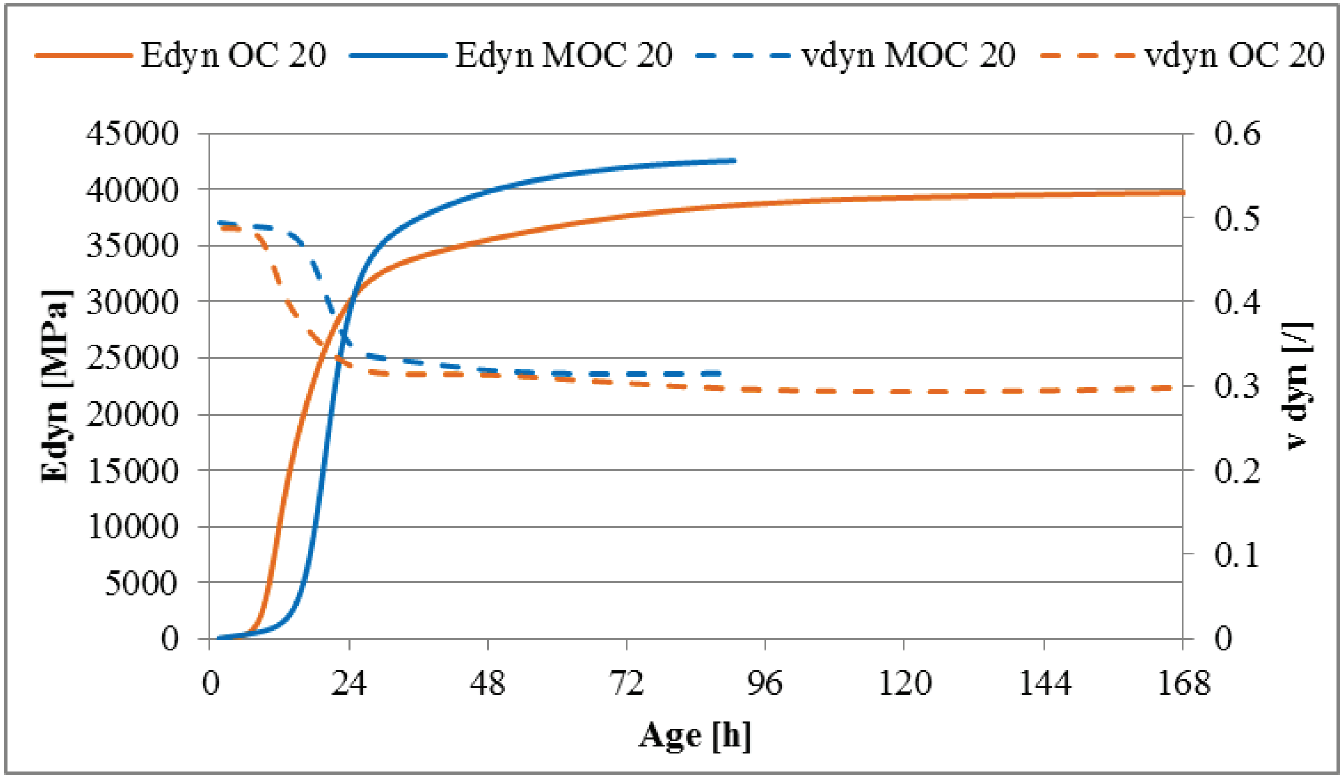
Carette J., Staquet S., Monitoring the setting process of mortars by ultrasonic P and S-wave transmission velocity measurement, Construction & Building Materials 94 (2015) 196-208.

Modified mixtures – determination of setting at ULB



	OC	MOC
Initial setting [h]	10.4	18.9
Final setting [h]	11.5	19.9

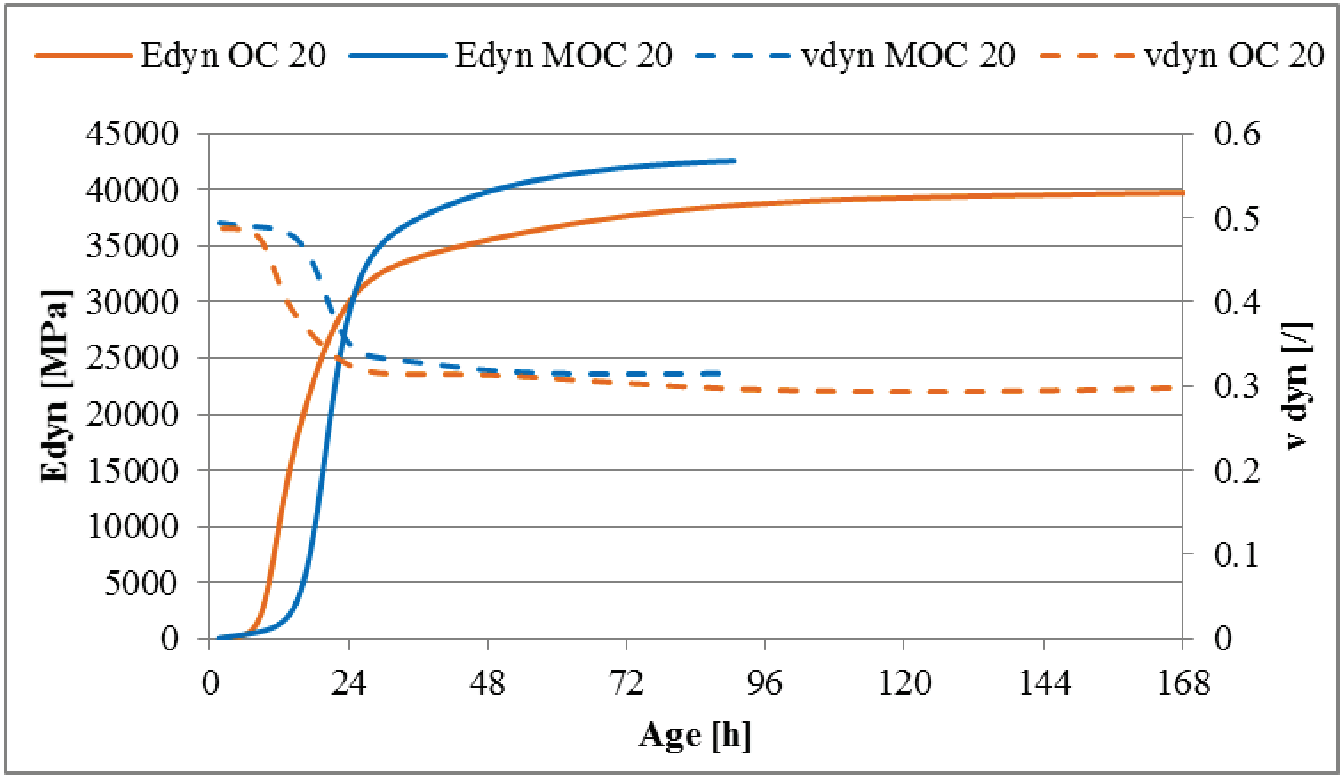
Modified mixtures – determination of setting at ULB



	OC	MOC	OM	MOM
Initial setting [h]	10.4	18.9	12.2	20.3
Final setting [h]	11.5	19.9	16.8	21.3

FreshCon

Modified mixtures – determination of setting at ULB



	OC	MOC	OM	MOM	CP	MCP
Initial setting [h]	10.4	18.9	12.2	20.3	15.8	20.3
Final setting [h]	11.5	19.9	16.8	21.3	18.8	21.5

FreshCon (OC, MOC, OM, MOM) — Vicat (CP, MCP)

2. Modified mixtures for RRT+ :

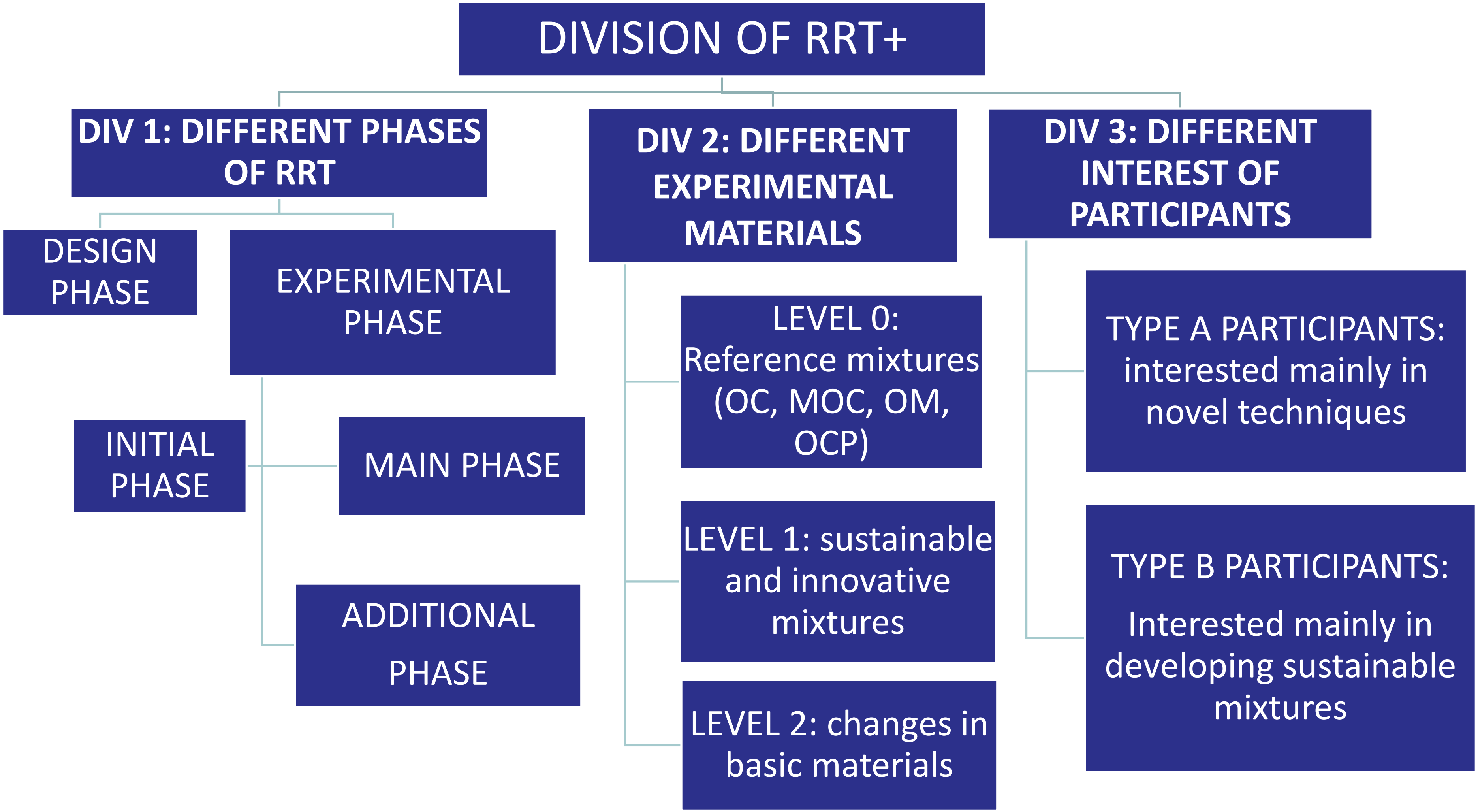
Concrete

Mortar

Cement Paste

for multi-scale modelling

RRT+ ORGANIZATION



RRT+ ORGANIZATION

- DIVISION OF RRT+
  - DIV 1: DIFFERENT PHASES OF RRT
    - DESIGN PHASE
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RRT+ participation commitment

42 laboratories in 18 European countries:

- Austria
- Belgium
- Croatia
- Czech Republic
- Great Britain
- Germany
- Great Britain
- Greece
- Hungary
- Malta
- Norway
- Poland
- Portugal
- Serbia
- Slovenia
- Spain
- The Netherlands
- Turkey

2 laboratories outside Europe

- Japan
- Canada

ca. 100 to. of requested raw material

- ca. 25 to. cement
- ca. 75 to. aggregates

Raw materials supply Funded by EDF

TU 1404 COST ACTION

Guimarães, 25-06-2015

COST TU 1404

www.tu1404.eu

Letter of commitment

With this letter, LEST/ISISE (Laboratory of Structures of the University of Minho) is expressing commitment to the RRT+ programme in the framework of COST action TU1404 entitled "Towards the next generation of standards for service life of cement-based materials and structures", in the following „COST Action" (www.tu1404.eu).

Article 1

General commitments

LEST/ISISE is committed to:

- performing all the tests marked in the tables below, in the scope of the Extended Round Robin test (in the following „RRT+") organized in the framework of Work Group 1 (WG1) of this COST Action,
- using materials for preparation of reference concrete mixes provided by COST Action,
- strictly following procedures for preconditioning and preparation of materials, as described in RRT+ document
- list and justify all deviations from the procedures described in the RRT+ document,
- providing the results of the tests in the required format for the purpose of a joint report, according to the described methods and phased timings mentioned in the RRT+ document.

Article 2

Participation expenses

Many of the financial and administrative efforts that arise from participation in this experimental program will be covered by the LEST/ISISE, and not by the COST Action. Please note that raw materials are provided - free of charge - by EDF, see http://fr.amiando.com/EDF-vercors-project.html. Even though COST TU1404 has a budget for transportation of the shared materials towards COST countries, this budget is limited and might not be enough to integrally cover all shipping expenses (mostly depending on the number of interested parties). In case the participating laboratories have to provide partial financial support to the shipping, it is not expected to surpass 300-400€.

1/2

TU 1404 COST ACTION

Article 3

Delivery of the shared materials

There is a possibility of selection of a single place in each country for delivery of the shared raw materials (as to decrease global costs). In this case, all participating laboratories from each country should agree on such address and take the responsibility of domestic transport. All countries are expected to get their experimental materials no later than October, 2015.

Article 4

Experimental results

LEST acknowledges that all of the results arising from the RRT are to be shared between all of the participants and will not be used without acknowledging efforts of this COST Action. It is further remarked that the contact person for LEST/ISISE is Miguel Azenha (miguel.azenha@civil.uminho.pt; +351938404554), who will be available for direct and swift interactions with the managing team on behalf of COST TU404.

Article 5

Application form

LEST/ISISE hereby confirms intention and capacity to perform all the tests indicated in the tables of the Application form (annex 1). The amount of the materials needed to adequately perform all the experiments is provided at the end of the form.

Article 6

Deadlines and sending the results

LEST/ISISE hereby confirms that all the results of RRT+ experimental programme will be sent via email to rrt@tu1404. The results must be included in suitable Excel spreadsheets prepared by Core Group of the COST Action. The results of the initial phase of the RRT+ experimental programme must be sent within 3 months after the reception of materials. Updated deadlines on the action will be given on the web site of COST TU1404 action.

Legal representative (Deputy director of ISISE/UM) – José Sena Cruz

Contact person – Miguel Azenha

Annexes:

- Application form

2/2

RRT+ material distribution

Canada

Japan

18 national contact points in Europe:
(COST supported)

- Austria
- Belgium
- Croatia
- Czech Republic
- France
- Germany
- Great Britain
- Greece
- Hungary
- Malta
- Norway
- Poland
- Portugal
- Serbia
- Slovenia
- Spain
- The Netherlands
- Turkey

direct delivery to intercontinental participants
(not COST supported)

kindly supported & performed by:

CEVA

Making business flow

Delivery size to national contact points

- Package 1
  - 1 palette of 64 bags cement / 1600 kg
  - Superplasticizer
    (at least 1 bottle of 5L for each lab per country)

+ Sika

SMN Société des Matériaux de Nogent

BUILDING TRUST Sika

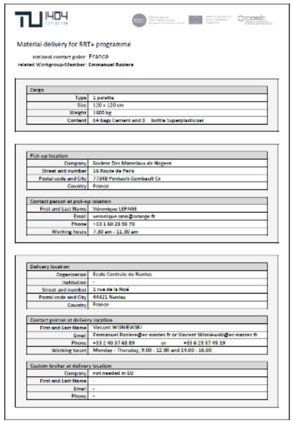
- Package 2
  - Aggregates in bigbags
  - basic size 700 kg or 1400 kg bigbags
    scaled to requested amount

x n

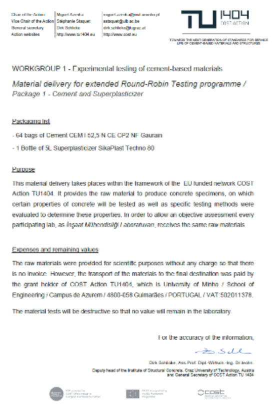
GSM Italcementi Group

Special documents & organization highlights

- Created documents for fluent processes

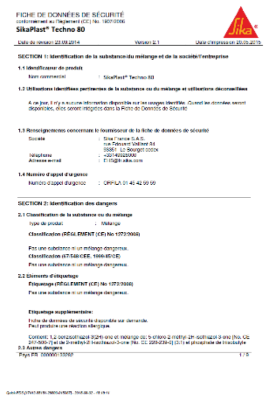


Material delivery for RRT+ programme



WORKGROUP 1 - Experimental testing of cement-based materials

Material delivery for extended Round-Robin Testing programme / Package 1 - Cement and Superplasticizer



FICHE DE DONNÉES DE SÉCURITÉ

SikaPlast® Techno 80

- data sheets
- declarations and pro-forma invoices for custom affairs
- material safety declarations
- chemical identity codes
- etc.

…

- Supply chain Japan
  - Standard transportation to CEVA Warehouse Hamburg, Germany
  - Repackaging according to requirements of sea freight
  - Vessel transportation to Nagoya harbor
  - Terminal handling and customs clearance in Japan
  - Domestic redistribution to final destination

Current status and Outlook

- 70 % of type 1 packages were picked up last week at the supplier
- A cautious estimate for the completion of distribution to all national contact points would be mid of October.

- Completion of domestic redistribution is desirable by Mid of November
  for professional support, feel free to contact your local quarter of CEVA www.**cevalogistics**.com

TU 1404
COST ACTION

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Vienna, September 20, 2015

TU 1404 COST ACTION

TOWARDS THE NEXT GENERATION OF STANDARDS FOR SERVICE LIFE OF CEMENT-BASED MATERIALS AND STRUCTURES

Sustainable and Innovative mixtures within RRT +

Stéphanie Staquet, sstaquet@ulb.ac.be

Luis Pedro Esteves, lupe@civil.aau.dk

Gregor Trtnik, Marijana Serdar, Miguel Azenha

European Science Foundation — ESF provides the COST Office through a European Commission contract

COST is supported by the EU Framework Programme

cost — European Cooperation in Science and Technology

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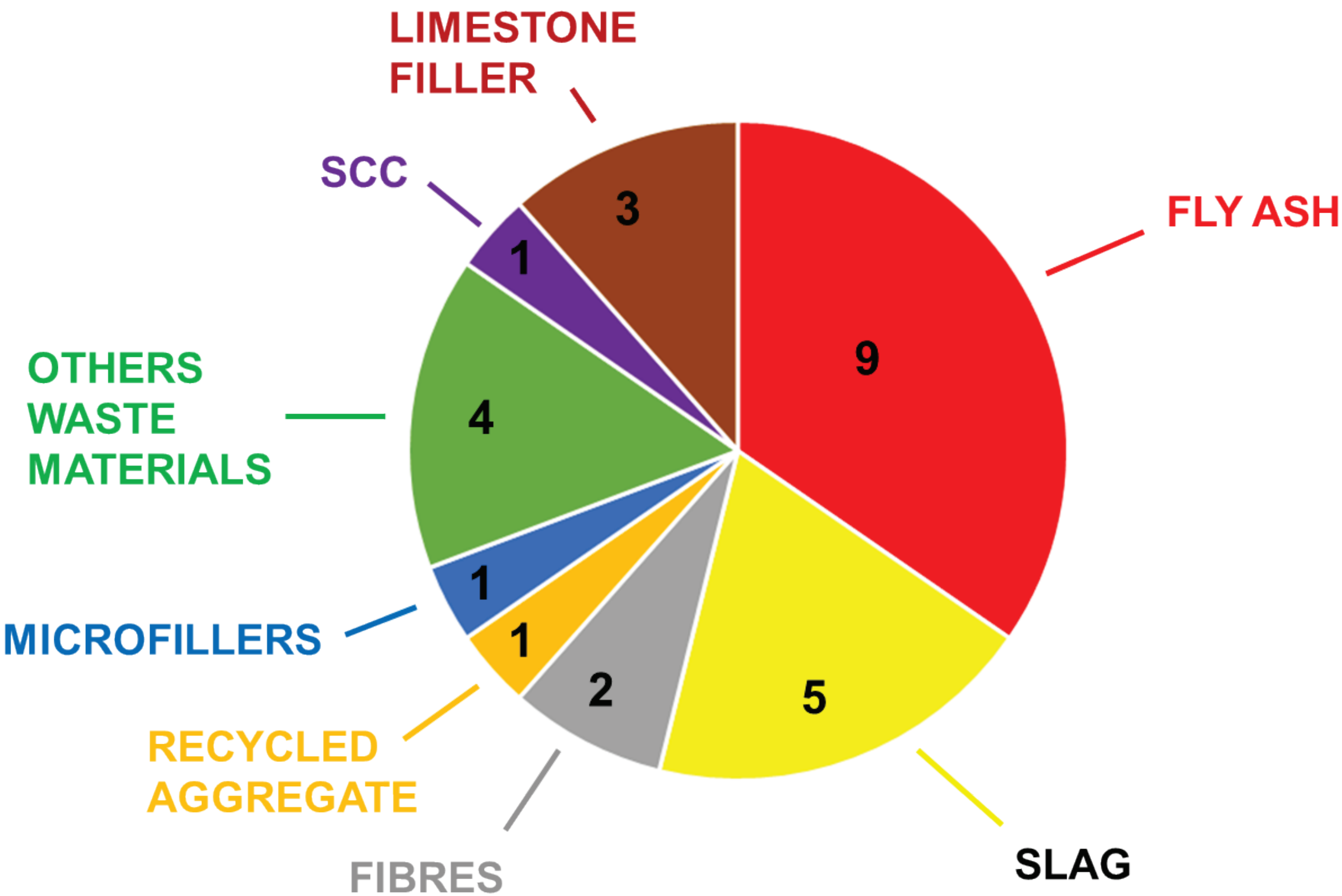
CLINKER ↔ CO_2 EMISSIONS
CRACKING RISK ↔ DURABILITY ISSUES
Sustainable and Innovative mixtures within RRT+

Sustainable and Innovative mixtures within RRT+

ISEL, High Institute of Engineering, Lisbon
OTH Regensburg
Ruben Paul Borg (Malta)
Belgian Building Research Institute (BBRI)
Graz University of Technology, Institute of technology and testing of building materials
GeM - Ecole Centrale de Nantes
KU leuven
Nantes University, GeM Institute
National Laboratory for Civil Engineering, Department for Materials (LNEC)
University of Coruna, Laboratory Ingenieria de la Construccion
University of Ljubljana, Faculty of Civil and Geodetic Engineering
Democritus University of Thrace, Department of Civil Engineering
Silesian University of Technology, Faculty of Civil Engineering
ULB Brussels
IGH Institute Zagreb
Budapest University of Technology and Economics, Department of Construction Materials and Technology
Yeditepe University, Department of Covol Engineering
Tu Delft, Microlab

18 labs !

Sustainable and Innovative mixtures within RRT+



Sustainable and Innovative mixtures within RRT+

GOAL : A clear image about the design approaches which are being pursued in EU countries to achieve low carbon concrete materials.

Sustainable and Innovative mixtures within RRT+

GOAL : A clear image about the design approaches which are being pursued in EU countries to achieve low carbon concrete materials.

Step further for type B participants:

1. What is the design approach that you will use to produce your eco-concrete material (mix proportioning)?

Sustainable and Innovative mixtures within RRT+

GOAL : A clear image about the design approaches which are being pursued in EU countries to achieve low carbon concrete materials.

Step further for type B participants:

1. What is the design approach that you will use to produce your eco-concrete material (mix proportioning)?
2. The selected eco-concrete produced must fit with the OC strength class or the MOC strength class.

Sustainable and Innovative mixtures within RRT+

Methodology

1. The strength class should be equivalent to the proposed standard and high-performance concrete being analysed in the RRT.
2. You should be able to demonstrate the durability class for the selected eco-concrete (from historic data).
3. You can use historic data to demonstrate point 1 or 2, but the approach should be validated by one test performed against the reference within the RRT.

Sustainable and Innovative mixtures within RRT+

Methodology

1. The strength class should be equivalent to the proposed standard and high-performance concrete being analysed in the RRT+.
2. You should be able to demonstrate the durability class for the selected eco-concrete (from historic data).
3. You can use historic data to demonstrate point 1 or 2, but the approach should be validated by one test performed against the reference mix OC or MOC within the RRT+.

→ Strength, density and air content would be the most relevant to test

1404
COST ACTION

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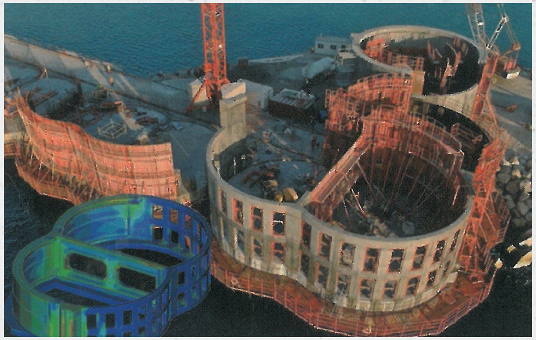
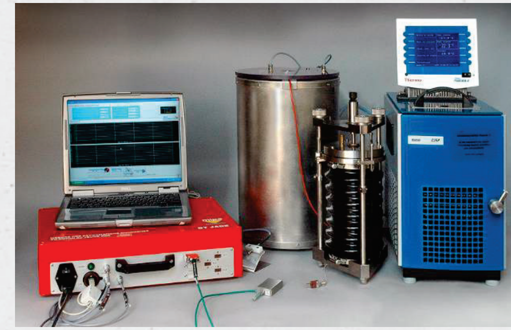


TU 1404 COST ACTION



Tasks inventory and organization for WG3: Development of recommendations and products to improve concrete structures serviceability

François Toutlemonde IFSTTAR

French Institute of Science and Technology for Transport, Spatial planning, Development and Networks

Terje Kanstad NTNU

The Norwegian University of Science and Engineering

2nd COST TU1404 Action Meeting – Vienna, September 19-20, 2015

WG3 Roadmap in COST TU1404 project

- Qualify experimental **devices** associated to control of early age properties in relation to serviceability (limit bias and scatter, ensure consistency with interpretation and modeling) : e.g. for conductivity, ultra-sonic strength measurement, shrinkage and thermal dilation, restraint-induced stresses and cracking
- Qualify **software** / associated design and computational methods related to prevention and control of early age cracking
- Prepare standard definition of relevant **specifications**: which parameters? Which threshold values? Classes (benchmarks / calibration)?
- Prepare draft (pre-standard) **test protocols** for determination of concrete characteristics related to serviceability: thermal expansion coefficient, autogenous shrinkage, moisture diffusion coefficient etc.
- Prepare pre-standard **methodologies** compatible with the Eurocode standard format to **address thermo-hydro-mechanical coupled effects on serviceability,** including early age and transient construction phases (curing, temperature development, restraint, viscoelasticity) and contribute to improvement of the material and execution standards
- Address the **various cases** of relevant structures, rafts, large industrial facilities, structures with tightness requirements, composite structures with restrained concrete parts, large structures built in successive phases, retrofitting situations etc.

WG3 Focus on restrained (early age) deformations and induced serviceability issues

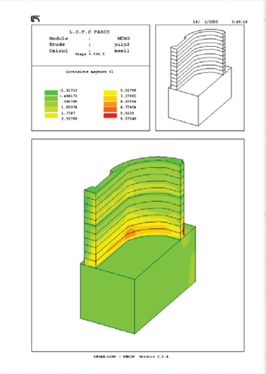
- Motivation

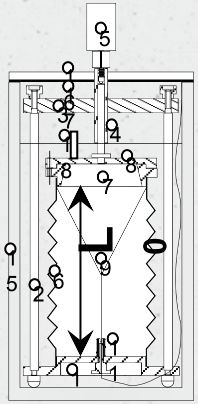
  - source of jobsite and implementation difficulties in a lot of cases: large industrial facilities, rafts, structures with tightness requirements, composite structures with restrained parts, large structures built in successive phases, retrofitting using concrete overlays…
  - agreement on principles, not on operational procedures
  - contradictory official guidelines (e.g. EN 1992, CIRIA C660)
  - relevant advances expected within WG1 (shrinkage measurement) and WG2 (numerical approach)
  - high expected impact
  - Complementary possible improvement of recommendations and standards, products, measurement devices and software

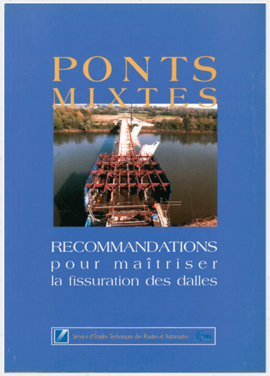
- Corresponding task inventory is already significant!

What is necessary?

- Early-age consideration in design:
  - Assumptions, specifications concerning early-age transient phases
  - Rules for design and SLS verifications
  - Associated validated software
- Determination of inputs:
  - Thermal strain potential (heat released) : method
  - Thermal expansion coefficient, thermal diffusion coefficient
  - E, fcc, fct, drying shrinkage at early age
  - Setting time (initiation of shrinkage) : direct & indirect methods / devices
  - Autogenous shrinkage from early age (method & devices)
  - Moisture diffusion coefficient
  - Creep or relaxation at early age
- Control and execution:
  - Maturity measurement (method & devices)
  - Crack measurement
  - Concrete specification regarding early age issues
  - Execution methods and requirements regarding early age







WG3 Tasks inventory and description

- Objectives
  - Identify the tasks and check consistency, exhaustiveness
  - Identify the associated TG within WG3, active volunteers for first input and volunteers for review and validation
  - Identify existing groups or committees to coordinate with
  - Identify existing background documents, prototype devices etc.
  - Prepare feasibility and priority classification
  - Launch the tasks (or some of them) after validation

- Your input will be required
  - Provide complementary description / background information
  - Fill in with your name as volunteer for draft preparation / draft review
  - Check the priority classification

WG3 Task 1 – TG3c, TG3d

- Output

  Revised **design assumptions** for SLS verifications including early age effects

- Task

  Revision of EN 1992 for combining thermal/chemical effects and loads for SLS crack verification

- Coordination with

  CEN TC250/SC2/WG1/TG7, CEN TC250/SC2/WG1/TG10

- Existing background, comments

  Background documents from CEOS.fr project and IFSTTAR-Vinci study.

  Opportunity of draft documents before EN standard?

WG3 Task 2 – TG3c

- Output

  Rules for design SLS verification (stresses, cracking) including early age restraint

- Task

  Informative annex for EN 1992 or separate document : constitutive laws, coupling laws, possible simplified approaches

- Coordination with

  CEN TC250/SC2/WG1/TG7, CEN TC250/SC2/WG1/TG10

  COST TU1404/WG2

  RILEM TC 254-CMS: Thermal cracking of massive concrete structures, Chair : E. FAIRBAIRN

- Existing background, comments

  Validated output from WG2 is required and shall be expressed in generic terms

WG3 Task 3 – TG3b

- Output

  Validated software for the early age/cracking verification

- Task

  Validation and documentation of a software or parts of a FE code associated to the SLS advanced verifications

- Coordination with

  COST TU1404/WG2

  RILEM TC 244-NUM: Numerical modelling of cement-based materials, Chair: K. VAN BREUGEL

  RILEM TC 254-CMS: Thermal cracking of massive concrete structures, Chair: E. FAIRBAIRN

- Existing background, comments

  Linked to the previous task. May require to establish a referential for code validation

WG3 Task 4 –TG3d

- Output

  Determination of inputs: **thermal strain potential**

- Task

  Approbation of standards in preparation: adiabatic and semi-adiabatic methods for determination of heat released by concrete during its hardening process

- Coordination with

  CEN TC104/SC1 (groups in charge of EN -12390 standards)

  RILEM TC 238-SCM: Hydration and microstructure of concrete with supplementary cementitious materials, Chair : N. DE BELIE

- Existing background, comments

  Isn't it too late? Standards under drafting, vote scheduled Aug. 2017

WG3 Task 5 – TG3c, TG3d

- Output

  Determination of inputs: thermal strains

- Task

  Development of standards for determination of the **thermal expansion coefficient** and the **thermal diffusion coefficient**

- Coordination with

  CEN TC104/SC1 (series of EN -12390 standards), COST TU1404/WG1

  RILEM TC 254-CMS: Thermal cracking of massive structures, Chair : E. FAIRBAIRN

- Existing background, comments

  Possible application of other generic standards?

WG3 Task 6 – TG3c, TG3d

- Output

  Determination of inputs: **E, fcc, fct at early age**

- Task

  Development of additives to NF EN 12390-2, NF EN 12390-3, NF EN 12390-6, NF EN 12390-13 with adaptation to early age

- Coordination with

  CEN TC104/SC1 (series of EN12390 standards)

  COST TU1404/WG1

- Existing background, comments

  Reliability / reproducibility information to be provided – dependency of fcc, fct with the thermal treatment beyond Arrhenius-type thermos-activation to be modeled?

WG3 Task 7 – TG3c, TG3d

- Output

  Determination of inputs: **setting time**, dormant period, initial time to take shrinkage into account

- Task

  Development of direct / indirect methods for determination of the setting time. Equivalence rules among the methods

- Coordination with

  CEN TC104/SC1 (series of EN12390 standards)

  COST TU1404/WG1

- Existing background, comments

  Influence of the temperature on this value is to be investigated

  Shall consider existing or prototype devices

WG3 Task 8 – TG3a

- Output

  Determination of inputs: **setting time**, dormant period, initial time to take shrinkage into account (**devices**)

- Task

  Development of optimized test devices (e. g. UPV, electric conductivity…) for direct / indirect determination of the setting time.

- Coordination with

  COST TU1404/WG1

- Existing background, comments

  Reliability / reproducibility / artefacts, market advantages to be quantified

  Prototypes do exist – Lessons of RILEM TC 195-DTD (points to take care of)

WG3 Task 9 – TG3c, TG3d

- Output

  Determination of inputs: **autogenous shrinkage from early age**

- Task

  Development of recommended / standardized method for autogenous shrinkage determination from early age. Equivalence rules among methods and devices?

- Coordination with

  CEN TC104/SC1 (series of EN12390 standards)

  COST TU1404/WG1

- Existing background, comments

  Influence of the temperature on this value is to be investigated

  Shall consider existing or prototype devices, Lessons of RILEM TC 195-DTD

WG3 Task 10 – TG3a

- Output

  Determination of inputs: **autogenous shrinkage from early age (devices)**

- Task

  Development of optimized test devices to determine autogenous shrinkage at early age

- Coordination with

  COST TU1404/WG1

- Existing background, comments

  Feedback of RRT conducted by RILEM TC 195-DTD

  Reliability / reproducibility / artefacts, market advantages to be quantified

WG3 Task 11 – TG3c, TG3d, possibly TG3a

- Output

  Determination of inputs: **drying shrinkage at early age**

- Task

  Development of recommended / standardized method for drying shrinkage determination from early age

- Coordination with

  CEN TC104/SC1 (series of EN12390 standards)

  COST TU1404/WG1

- Existing background, comments

  Shall consider existing or prototype devices. Equivalence rules among methods and devices?

WG3 Task 12 – TG3c, TG3d, possibly TG3a

- Output

  Determination of inputs: **moisture diffusion coefficient**

- Task

  Development of recommended / standardized method for determination of moisture diffusion from early age (indirect method ? Controlled drying ? Interaction with cracking ?)

- Coordination with

  CEN TC104/SC1 (series of EN12390 standards)

  COST TU1404/WG1

  RILEM TC MCT: Multi-component transport and chemical equilibrium in cement-based materials, Chair: B. JOHANNSSON

- Existing background, comments

WG3 Task 13 – TG3c, TG3d, possibly TG3a

- Output

  Determination of inputs: **creep or relaxation at early age**

- Task

  Development of recommendations / appendices to existing standards

- Coordination with

  CEN TC104/SC1 (series of EN12390 standards)

  COST TU1404/WG1

- Existing background, comments

WG3 Task 14 – TG3c, TG3d

- Output

  Control methods: direct / indirect **maturity measurement**

- Task

  Development of recommendations / additions to the execution standard

- Coordination with

  CEN TC104/SC2 (in charge of EN 13670)

- Existing background, comments

  Existing French recommendations

WG3 Task 15 – TG3a, TG3b

- Output

  Control methods and devices: **maturity measurement (devices and processing tool)**

- Task

  Possible development of maturity measurement devices and processing software

- Coordination with

  COST TU1404/WG1

- Existing background, comments

WG3 Task 16 – TG3c, TG3d, possibly TG3a

- Output

  Control methods: **crack measurement**

- Task

  Development of recommendations/pre-standards for crack control

- Coordination with

  CEN TC104/SC2 (in charge of EN 13670)

- Existing background, comments

  Major acceptability issue

  Possible indirect methods when tightness requirements?

WG3 Task 17 – TG3c, TG3d

- Output

  Performance-based **concrete specification addressing early-age issues**

- Task

  Revision of EN206 including specifications, target or threshold values

- Coordination with

  CEN TC104/SC1, COST TU1404/WG1

- Existing background, comments

  Only when standards for determination of specified performance (e.g. autogenous shrinkage…) are available

WG3 Task 18 – TG3c, TG3d

- Output

  Execution methods, prevention of early age issues impairing serviceability

- Task

  Revision of EN 13670 including recommended procedures, possible specifications associated to execution

- Coordination with

  CEN TC104/SC2 (in charge of EN 13670)

- Existing background, comments

Priority actions among the targeted objectives

- Based on availability of identified volunteers:
  - For draft documents preparation
  - For prototype devices or software definition and realization
- Based on output production maturity:
  - Existing background material (possibly from WG1 & WG2)
  - Existing groups having common interest
  - Existing demand, end-users, market for using the output
- Priority definition shall keep technical consistency of the production within WG3
- Use of background data shall take care of control of concreting process (quality insurance, documentation)

Targeted objectives for next year(s)

- Sub-groups for targeted priority actions based on identified volunteers:
  - Deadline for application: October 15th, 2015
  - Formal definition of sub-groups and roadmap: November 15th, 2015
  - Launching of the actions: before end of 2015
- Milestone for these sub-groups:
  - First prototype of the expected product or first draft of the expected deliverable (recommendation, pre-standard document): August 15th, 2016
  - Deadline for expression of comments and proposed improvements: December 15th, 2016
  - Improved versions of products and documents addressing these remarks: April 15th, 2017

Next events for WG3

- COST TU1404 3rd Workshop at mid-2016:
  - Possibly connected to RILEM's Week (Lyngsby, Denmark, August 21-24)
  - Alternatively: connected to CONSEC'2016 (Lecco, Italy, September 12-14)
  - Alternatively: in an inclusiveness country: Portugal ?
- Main expectations for WG3 during this workshop:
  - Presentation of the first prototypes of the expected product or first drafts of the expected deliverable (recommendation, pre-standard documents)
  - Discussion before enquiry for expression of comments and proposed improvements, interaction with WG1 and WG2
- Next milestone: JCI-RILEM Workshop in Tokyo, April 23-24, 2017
  - Presentation of improved versions and discussion, in relation with revised JCI Guidelines on control of thermal cracking

TU 1404
COST ACTION

Back to the list of presentations

TU 1404 COST ACTION

MULTI-SCALE MODELLING OF CEMENT PASTE AND CONCRETE: FROM MICROSTRUCTURE EVOLUTION TO DEFORMATIONS

Enrico Masoero – Newcastle University, United Kingdom

Newcastle University

CO-AUTHORS

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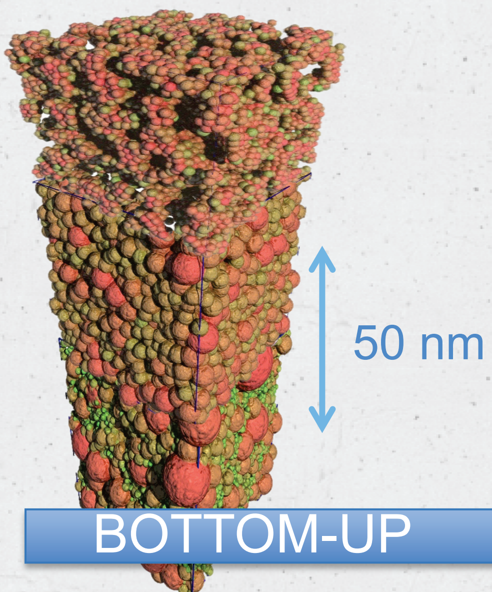
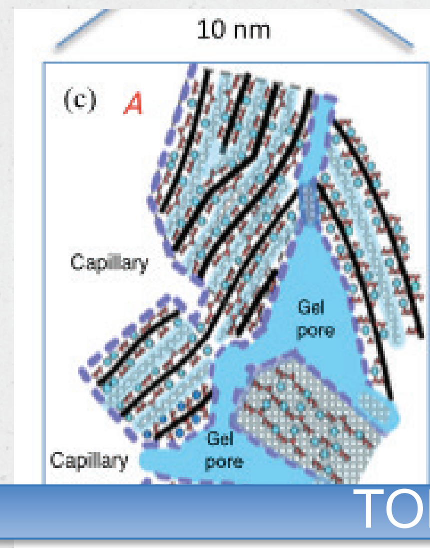
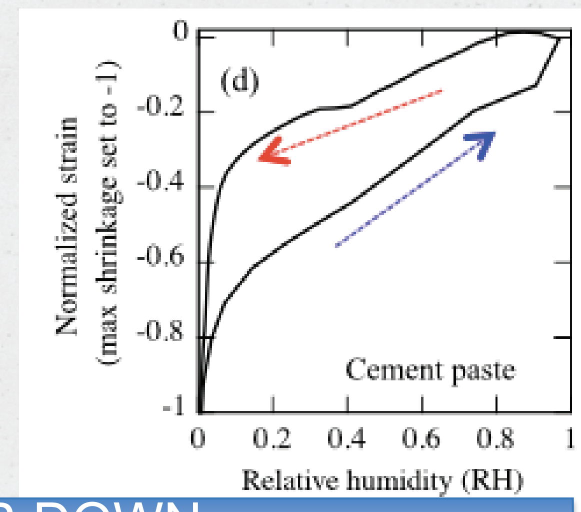
Katerina Ioannidou – Massachusetts Institute of Technology, U.S.A.
Hamlin M. Jennings – Massachusetts Institute of Technology, U.S.A.
Hegoi Manzano – Universidad del Paìs Vasco, Spain
Roland J.-M. Pellenq – Massachusetts Institute of Technology, U.S.A.
Matthew B. Pinson – University of Chicago, U.S.A.
Jeffrey J. Thomas – Schlumberger-Doll Research, U.S.A.
Franz-Josef Ulm – Massachusetts Institute of Technology, U.S.A.
Sidney Yip – Massachusetts Institute of Technology, U.S.A.

CONTENT

- Cement hydration and concrete degradation
- The challenge of timescale
- <u>Bottom-up</u>: Kinetic simulations of cement hydrates formation
- <u>Top-down</u>: hysteresis from multiscale porosity: modelling sorption and shrinkage
- Where do bottom-up and top-down meet?





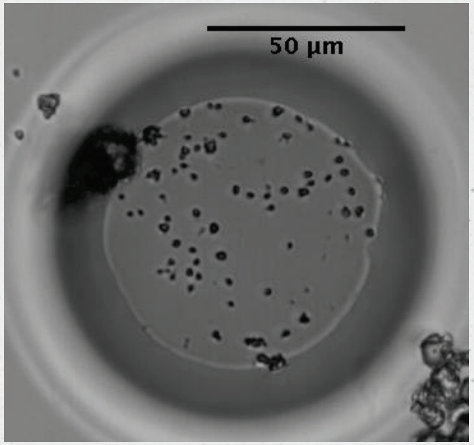


BOTTOM-UP

TOP-DOWN

CEMENT HYDRATION, CONCRETE DEGRADATION

Hydration & setting



Courtesy of Dr R Grossier, CNRS Marseille France

Creep

Bazant ZP et al., J Struct Eng, 2012

Drying shrinkage

Freeze-thaw …

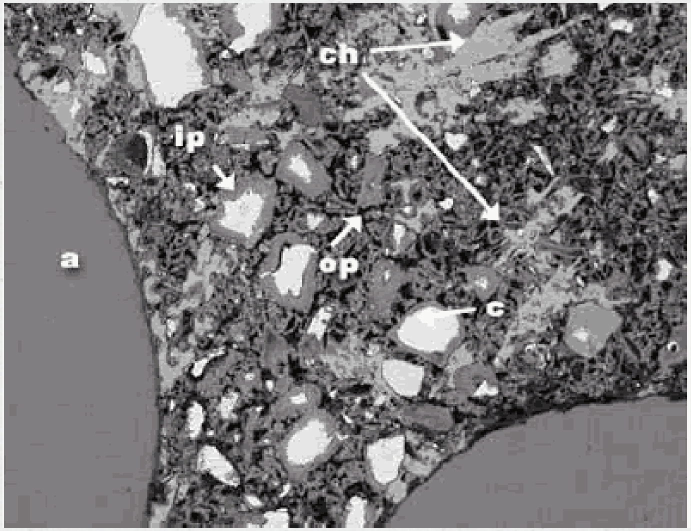
http://www.ndtoolbox.org/contet/bridge/concrete-deterioration-description

- Concrete degradation is often the macroscopic manifestation of nanoscale processes, such as chemical reactions, nanoscale shear deformations, fluid pressure in nanopores

CEMENT HYDRATION, CONCRETE DEGRADATION

Cement paste micrograph

~1 μm



a = aggregate

c = unreacted cement grains

ch = calcium hydroxide

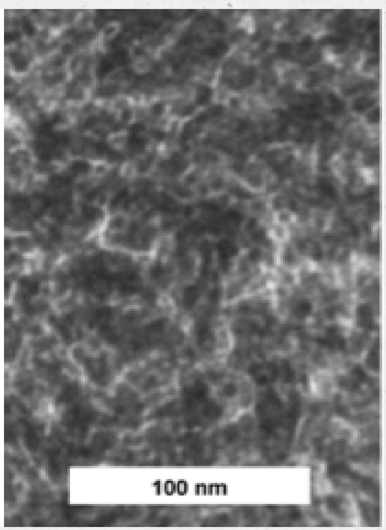
ip,op= calcium silicate hydrate **C-S-H** (“inner” and “outer” product)

https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/04150/images/fig185.gif

- The C-S-H is the most abundant phase in ordinary cementitious materials. It is the “glue” of ordinary cement pastes and controls largely the long-term performance of the material.

CEMENT HYDRATION, CONCRETE DEGRADATION

Transmission Electron Microscopy (TEM)

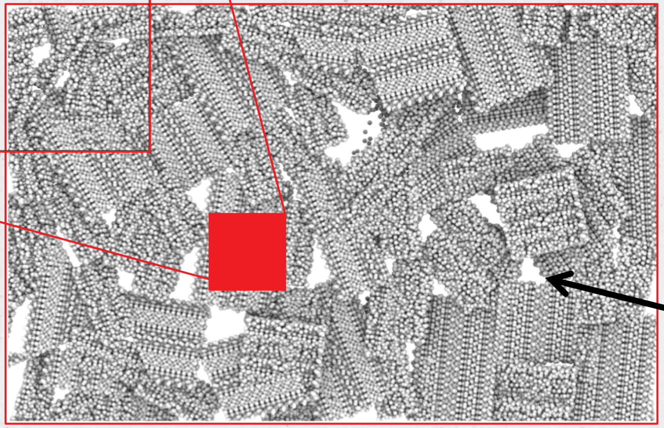


I.G. Richardson, Cem. Concr. Res., (2004)

1 nm

Bonnaud et al. Soft Matter 2013

*Manzano, **Masoero** et al, Soft Matter 2013*



5 nm

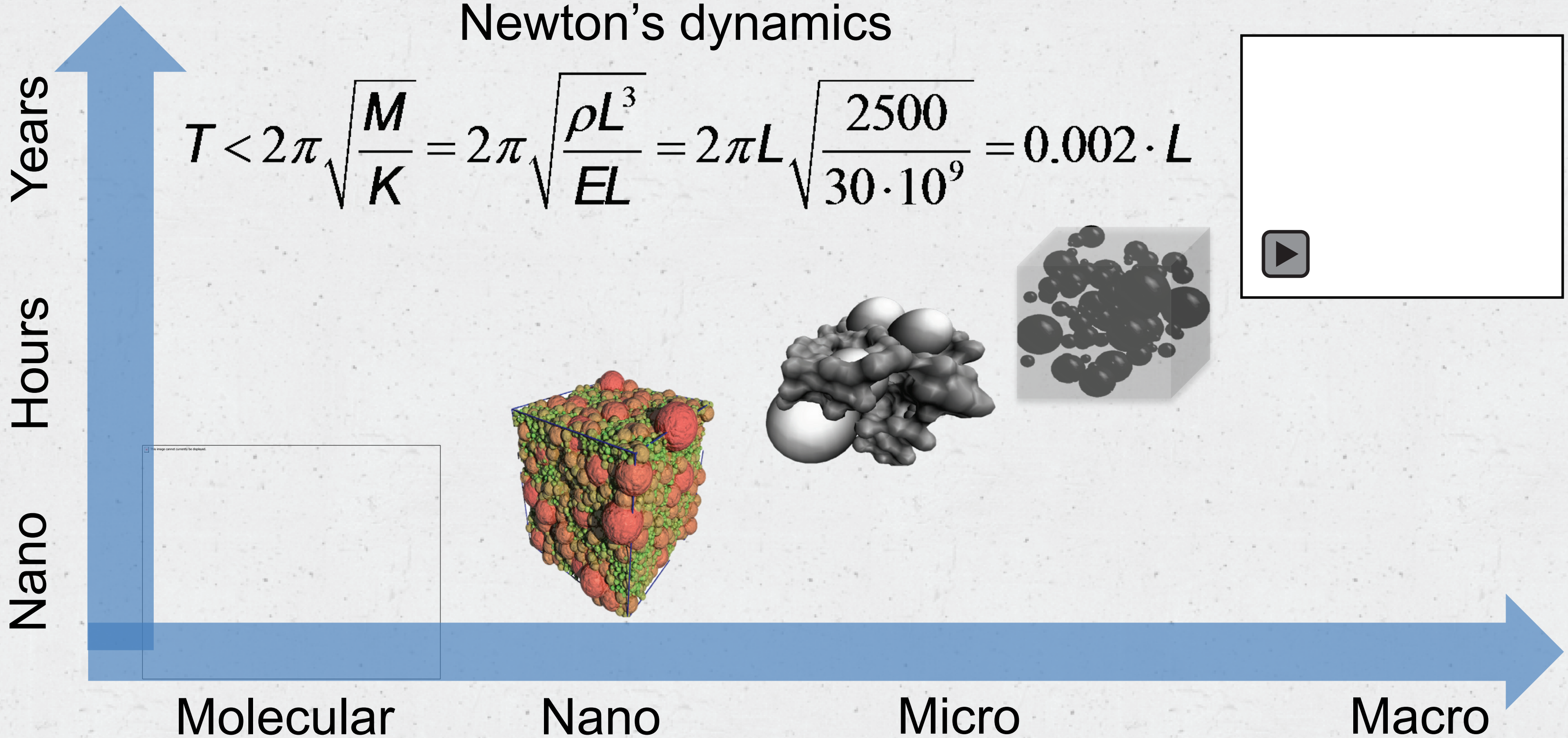
Gel pore (1-50 nm)

- The C-S-H is a mesoporous materials made of a disordered assembly of ~5nm units, whose molecular structure consists of a stack of calcium-silicate layers and water layers

THE CHALLENGE OF TIMESCALE

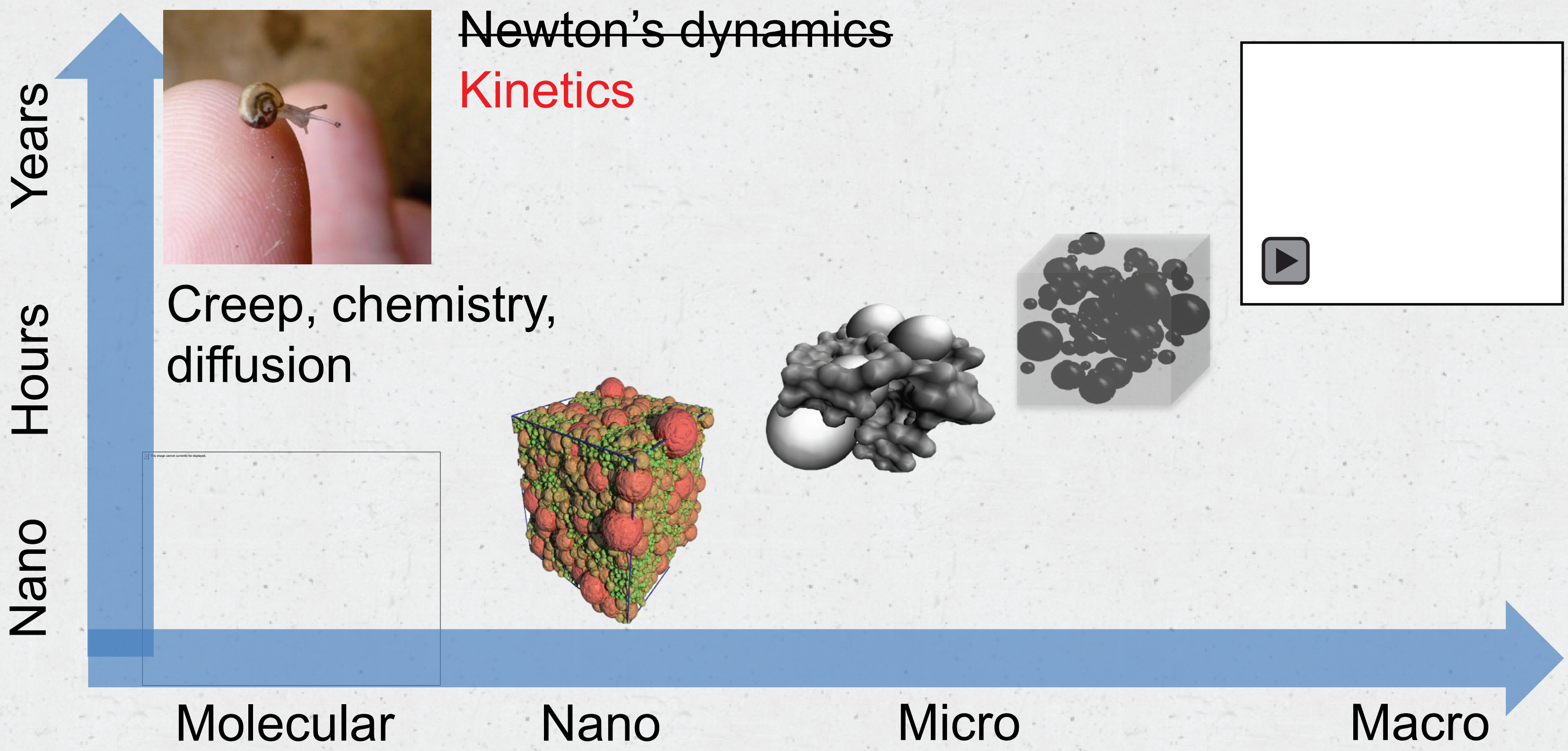
Newton's dynamics

$$T < 2\pi\sqrt{\frac{M}{K}} = 2\pi\sqrt{\frac{\rho L^3}{EL}} = 2\pi L\sqrt{\frac{2500}{30\cdot 10^9}} = 0.002\cdot L$$



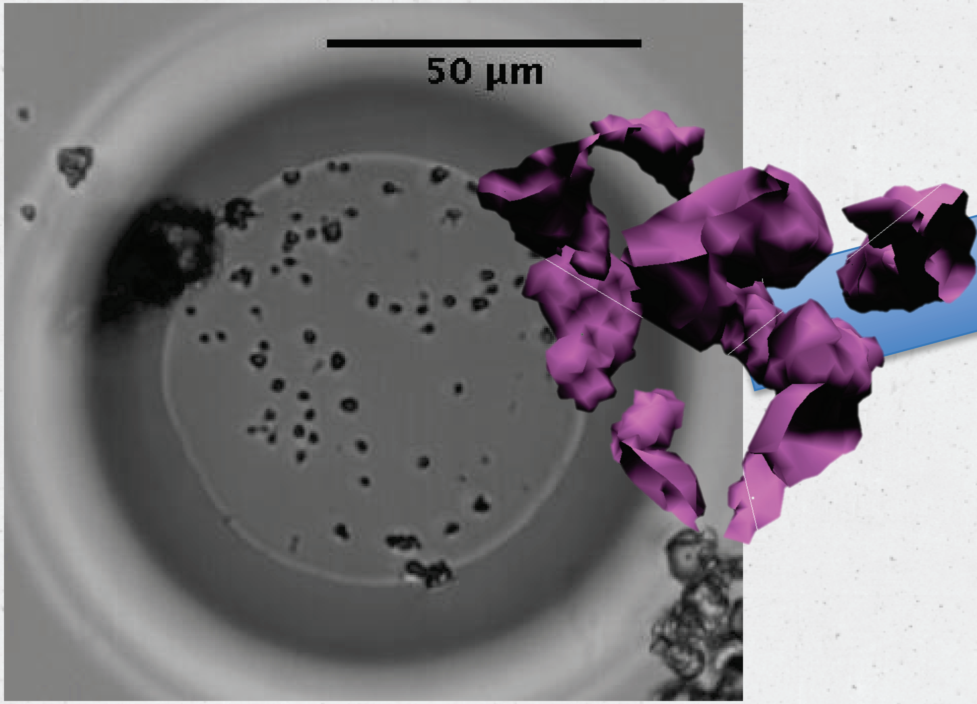
- Simulations based on integrating Newton's equations of motion imply that the addressable timescale is bounded by the length-scale. However …

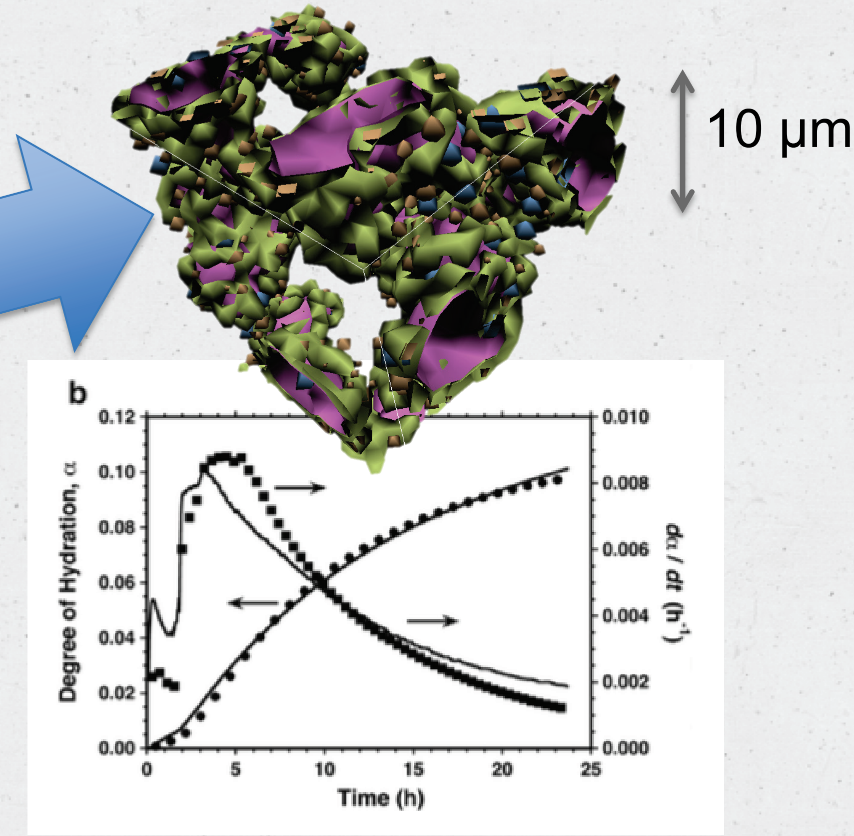
THE CHALLENGE OF TIMESCALE



- … hydration and degradation imply mechanisms with nano-length-scale and very long time scales. A paradigm-shift to kinetics is proposed here.

KINETIC SIMULATIONS OF CEMENT FORMATION

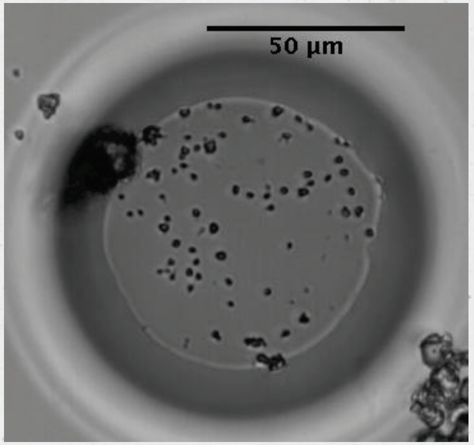


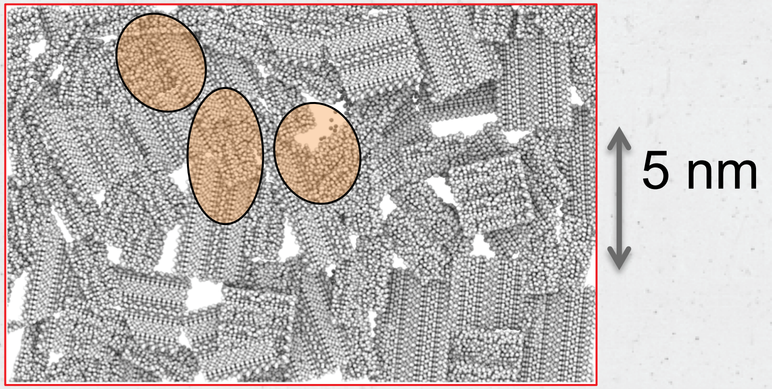


Bullard et al, Cem Concr Res (2015)

- Microstructure evolution is determined by phase-specific parameters at the sub-micrometer scale, which require nanoscale models of the hydrates

KINETIC SIMULATIONS OF CEMENT FORMATION



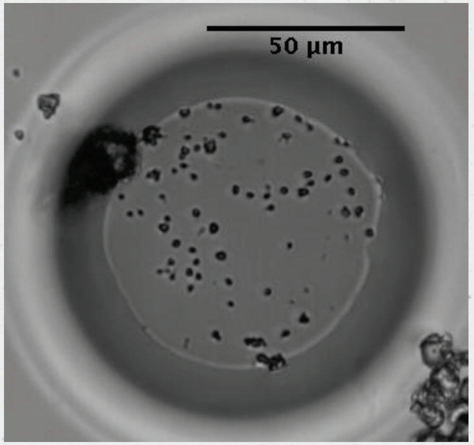


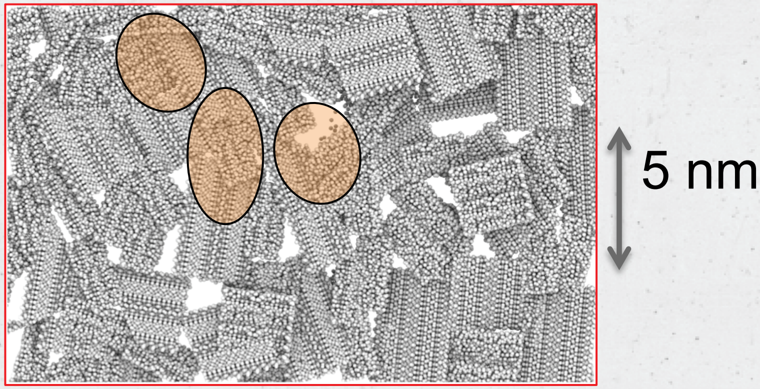
Coarse-grained mesoscale approach

Assumption 1: C-S-H can be discretised as nanoparticles with diameter ~5nm (“Colloid model”: Jennings, Cem Concr Res, 2000)

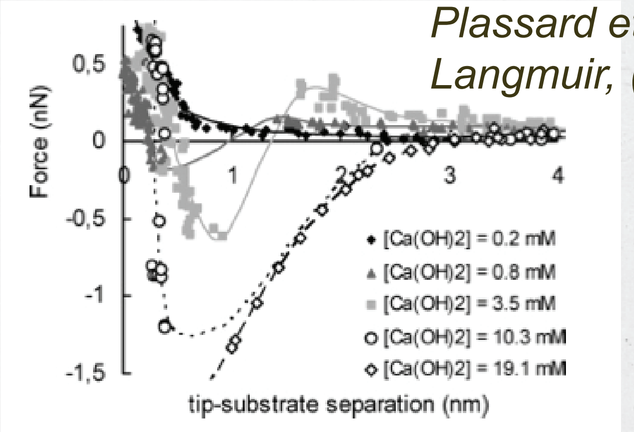
- The kinetic formulation of C-S-H formation at the mesoscale of ~500 nm relies on three assumptions

KINETIC SIMULATIONS OF CEMENT FORMATION





Coarse-grained mesoscale approach

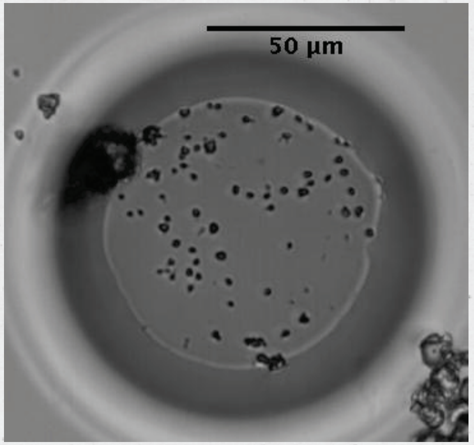


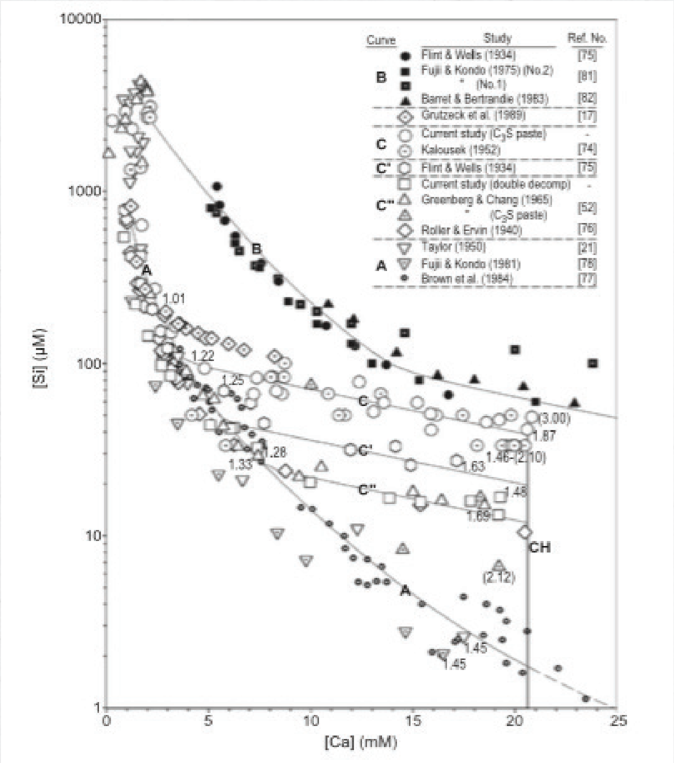
Plassard et al, Langmuir, (2009)

Assumption 2: The colloids interact according to force-distance laws (e.g. from AFM experiments or molecular simulations)

- The kinetic formulation of C-S-H formation at the mesoscale of ~500 nm relies on three assumptions

KINETIC SIMULATIONS OF CEMENT FORMATION





Chen et al, Cem Conr Res (2004)

Coarse-grained mesoscale approach

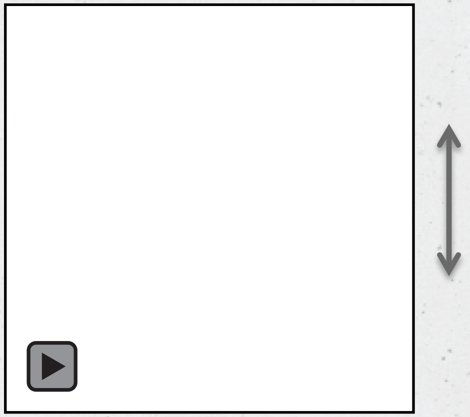
Assumption 3: The thermodynamic limit applies already at this mesoscale

- The kinetic formulation of C-S-H formation at the mesoscale of ~500 nm relies on three assumptions

KINETIC SIMULATIONS OF CEMENT FORMATION

Kinetic Monte Carlo

Define a set of events that modify the colloids: nucleation, growth, dissolution



Rate of the ith possible event:

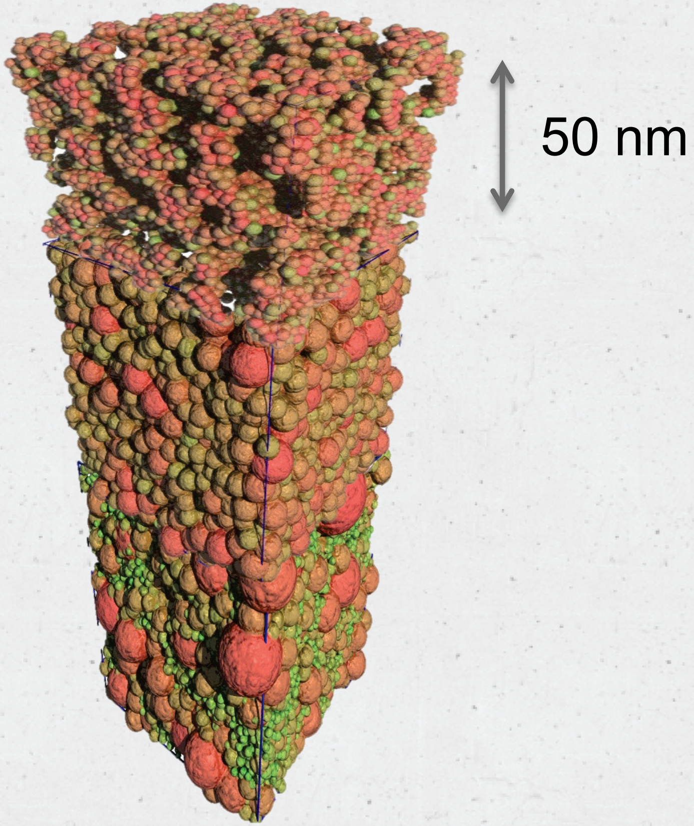
$$R_i = \upsilon e^{\left(-\Delta G_i^* / k_B T\right)} e^{\left(-\Delta U_i / k_B T - \Delta G_i / k_B T\right)}$$

ΔG = solution free energy change due to event i (from thermodynamics)

ΔU = interaction energy change due to interparticle interactions

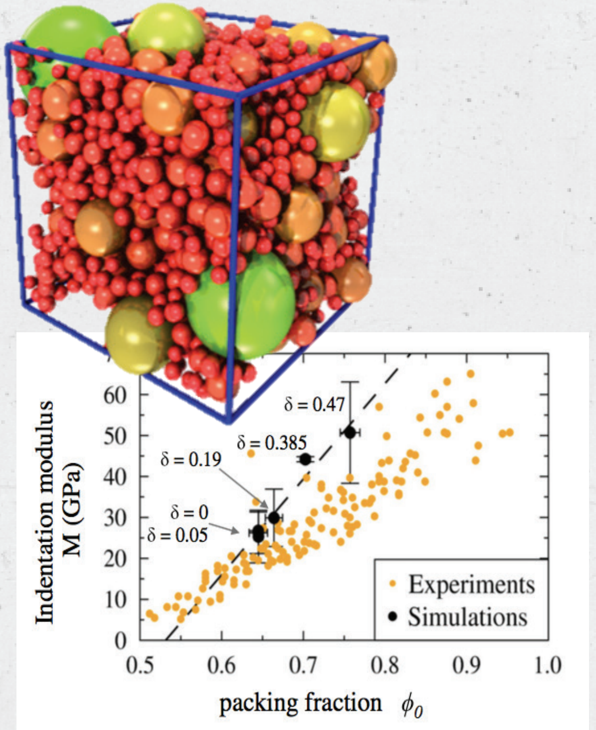
- In the kinetic theory, the rate of an event depends on the energy scale and is *not* bounded by the length scale.
- The presence of both ΔU and ΔG in R couples chemistry with mechanics.
- The pre-factor is often innocuous, buy not always (beyond our scope here)

KINETIC SIMULATIONS OF CEMENT FORMATION

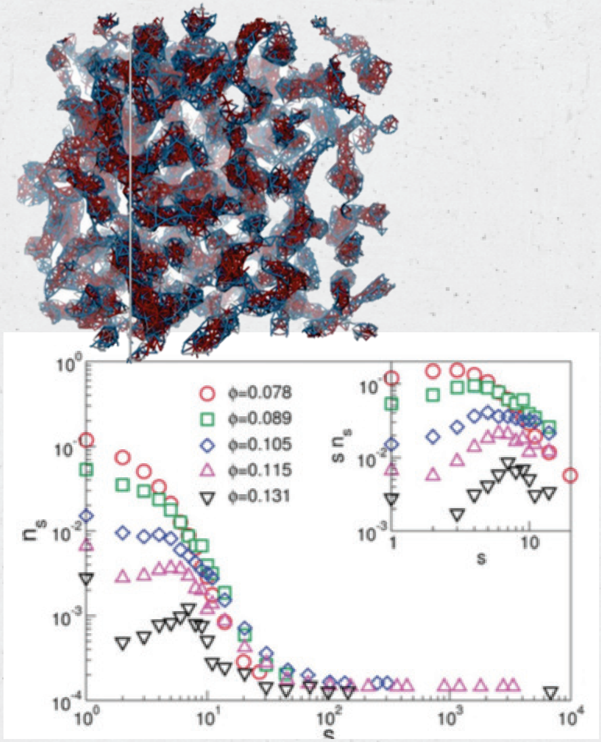


- The proposed kinetic approach provides model C-S-H gel structures that form in long timescales (like hydration) and depend on the solution chemistry

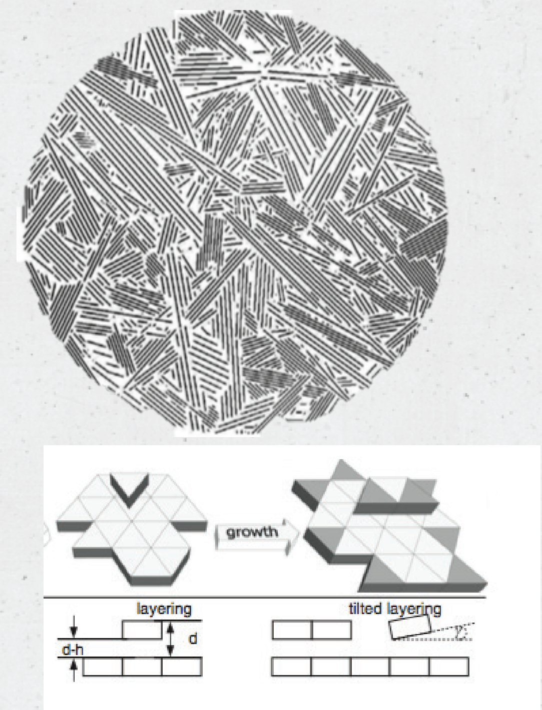
KINETIC SIMULATIONS OF CEMENT FORMATION



***Masoero** et al, Physical Review Letters (2012)*



Ioannidou et al, Soft Matter (2014)



Etzold et al, Cem Concr Res (2014)

- Kinetic simulations are just starting now, but several authors have already mimicked precipitation to get C-S-H mesostructures and extract properties

HYSTERESIS FROM MULTISCALE POROSITY

PHYSICAL REVIEW APPLIED **3**, 064009 (2015)

Hysteresis from Multiscale Porosity: Modeling Water Sorption and Shrinkage in Cement Paste

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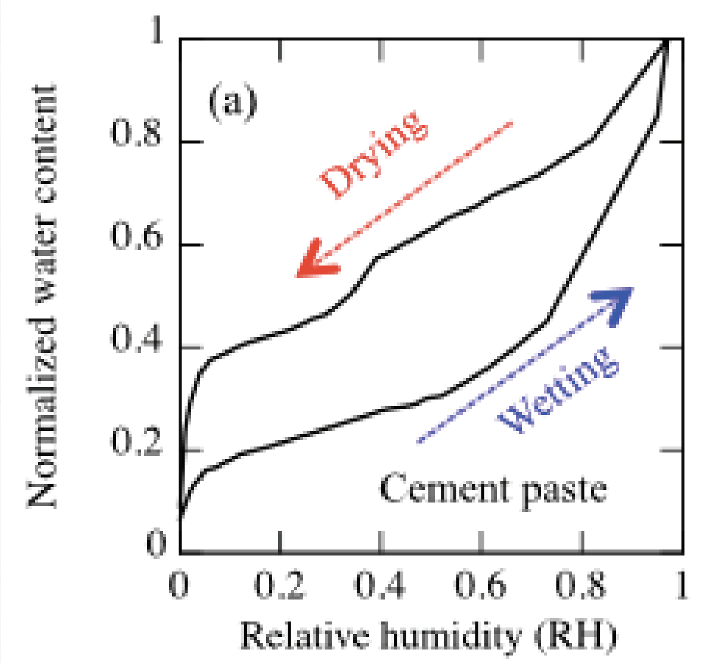
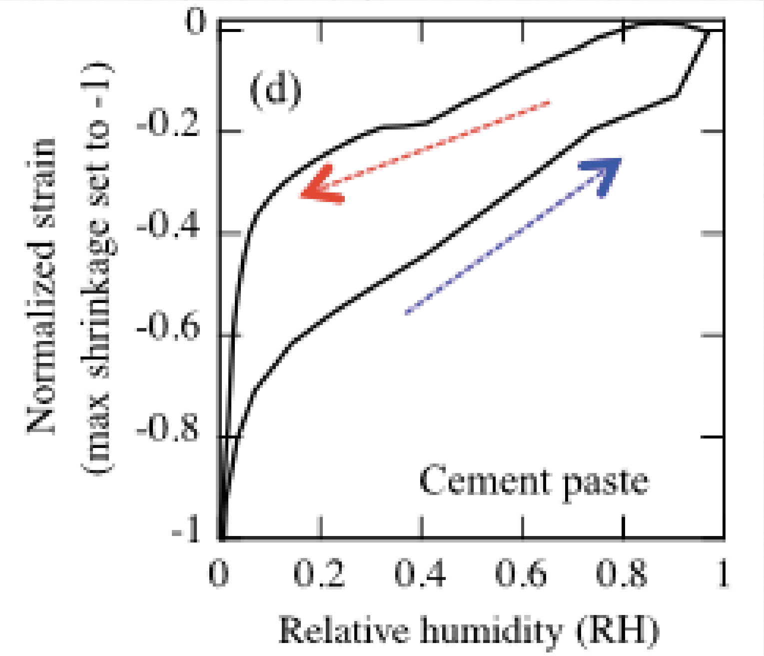
(Received 2 September 2014; revised manuscript received 29 January 2015; published 17 June 2015)

Hamlin M Jennings
(1946-2015)

HYSTERESIS FROM MULTISCALE POROSITY

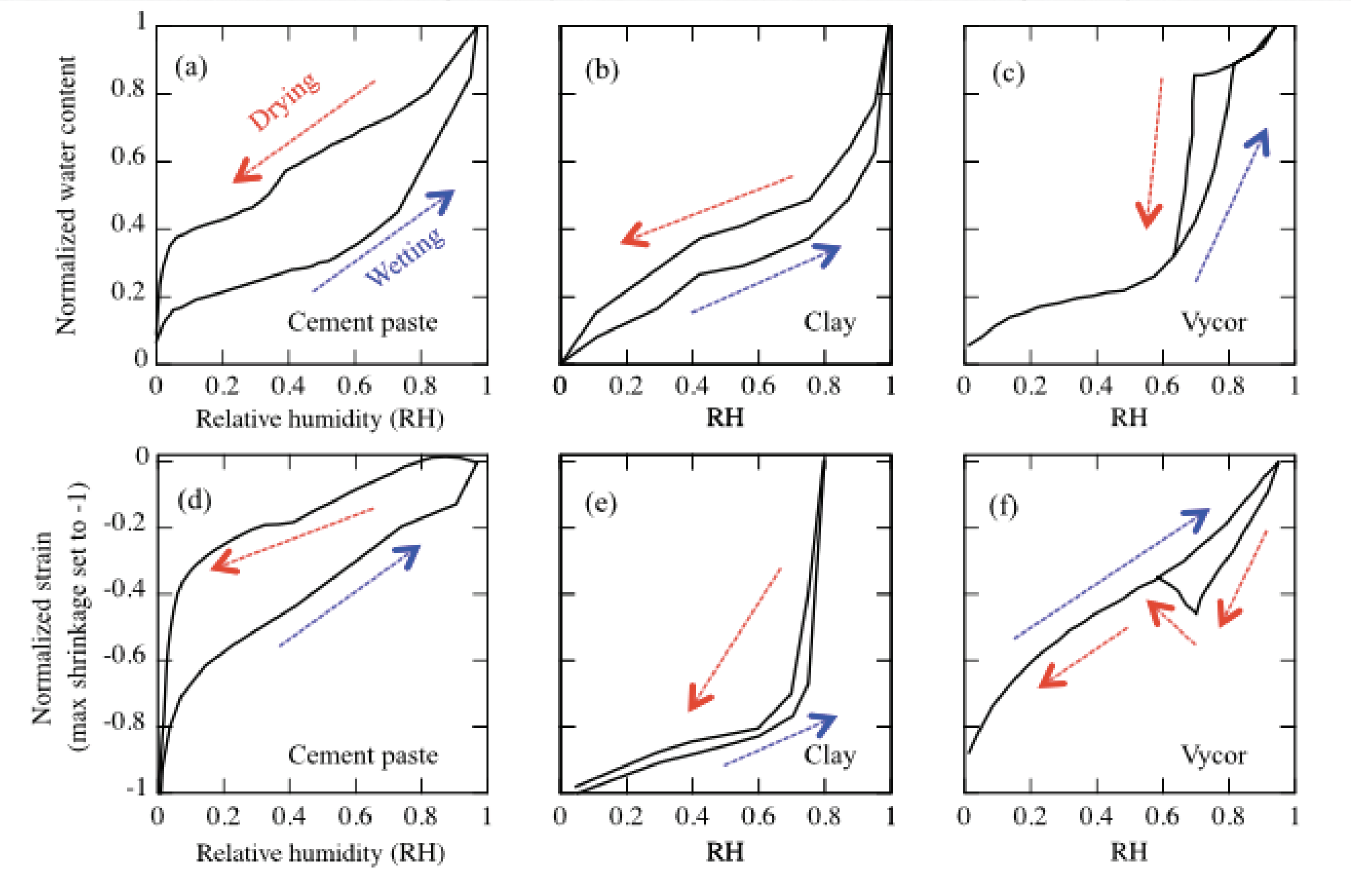




Feldman RF et al, Mater Constr (1968)

- Water vapour adsorption/desorption and corresponding shrinkage/swelling (mature cement paste, 2nd cycle onward): both are hysteretic.
- Below 99% RH, all the pores larger than 100 nm are empty → macroscopic shrinkage is almost entirely caused by nanopore fluid pressure

HYSTERESIS FROM MULTISCALE POROSITY



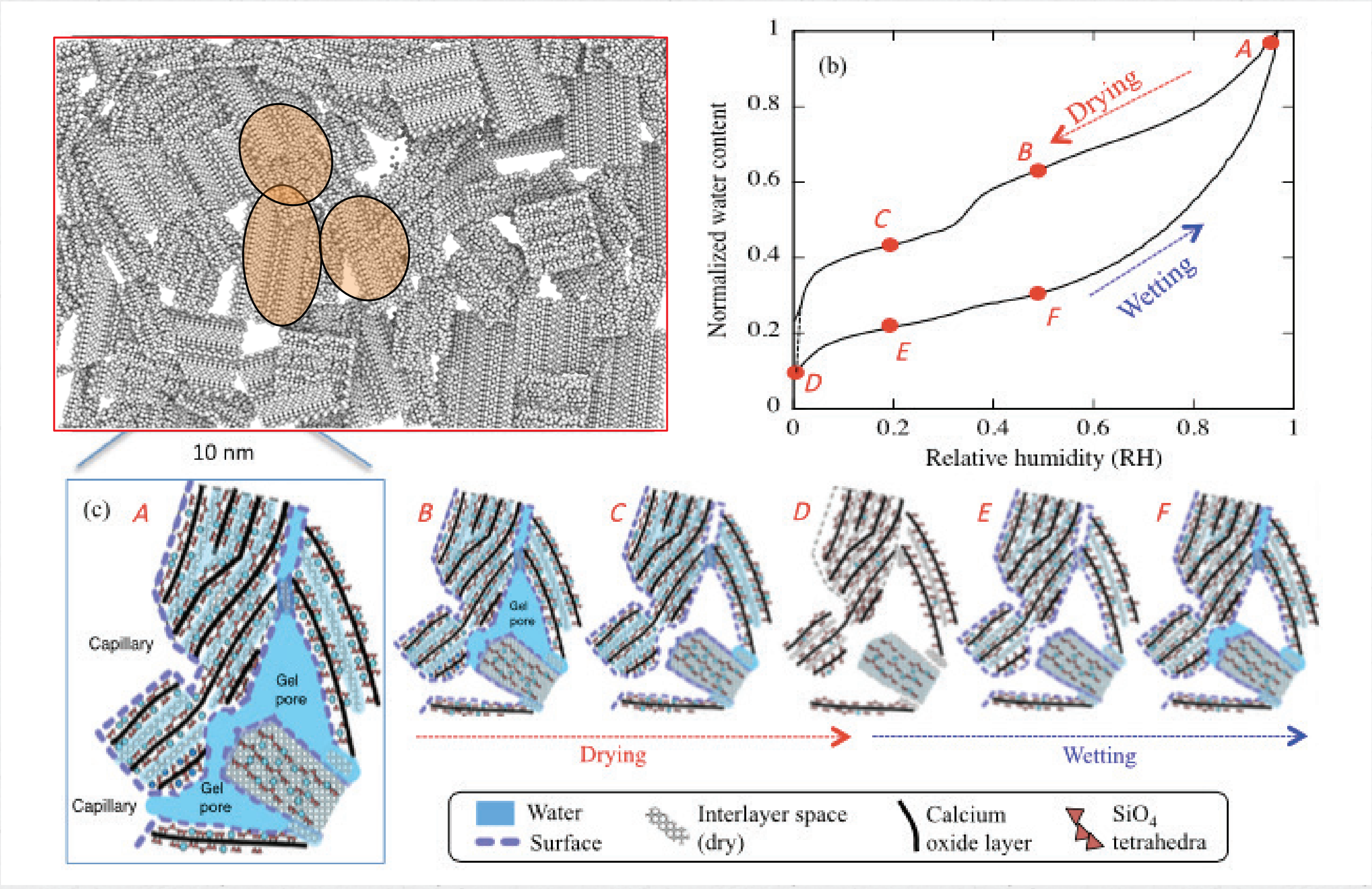
Pinson MB, **Masoero E** et al, Phys Rev Appl (2015)

Cases JM et al, Mater Clays Clay Miner(1997)

Haines RS et al, J Chem Phys (1947)

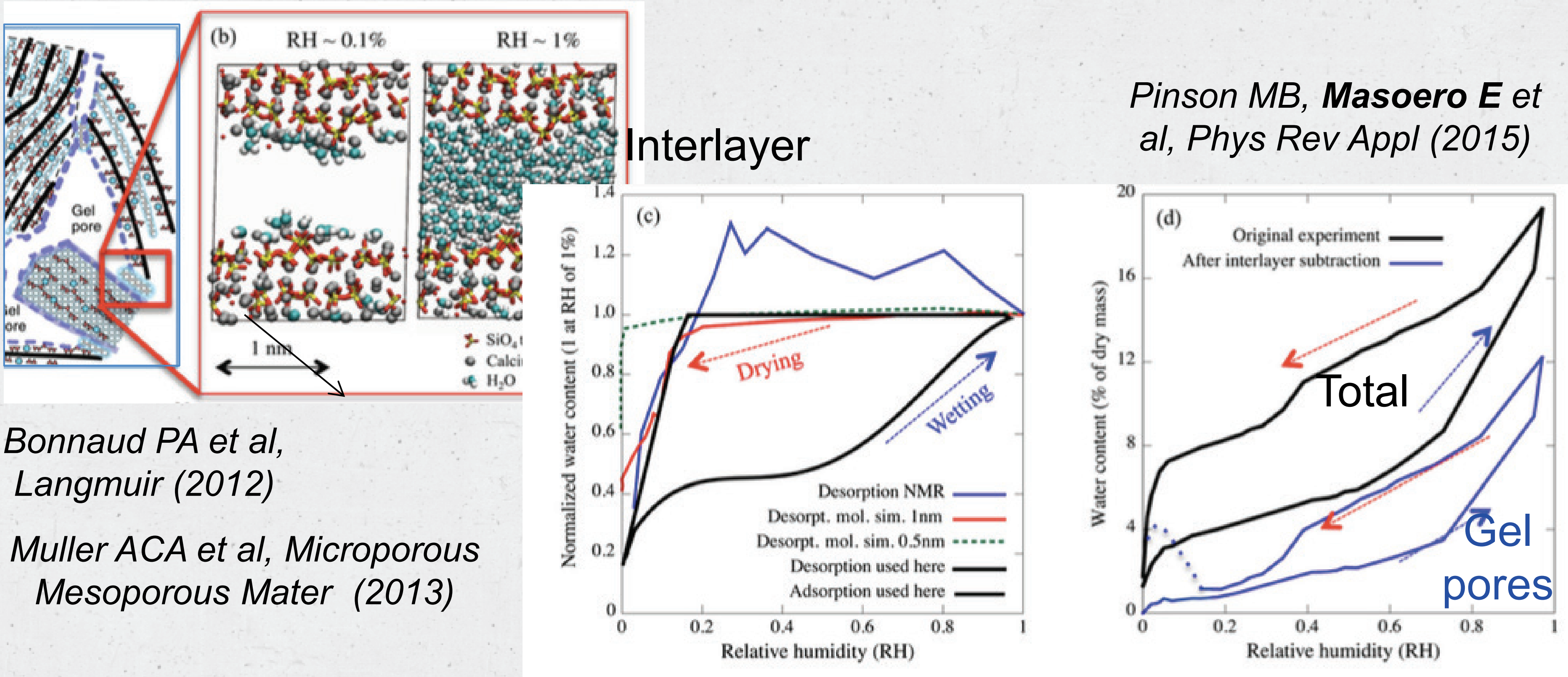
- The cement paste behaves in-between swelling clay and mesoporous glass. This is consistent with its nano-pore structure: see next page

HYSTERESIS FROM MULTISCALE POROSITY



- The sorption isotherm is the convoluted result of water in interlayer spaces (<1 nm) and gel pores (>1 nm), which enter-leave at different RH

HYSTERESIS FROM MULTISCALE POROSITY



*Pinson MB, **Masoero E** et al, Phys Rev Appl (2015)*

Bonnaud PA et al, Langmuir (2012)

Muller ACA et al, Microporous Mesoporous Mater (2013)

- Results from experiments and molecular simulations suggest a sorption isotherm for interlayer water only (<1nm). This can be subtracted from the total sorption isotherm to obtain a reduced isotherm for gel-pore water only

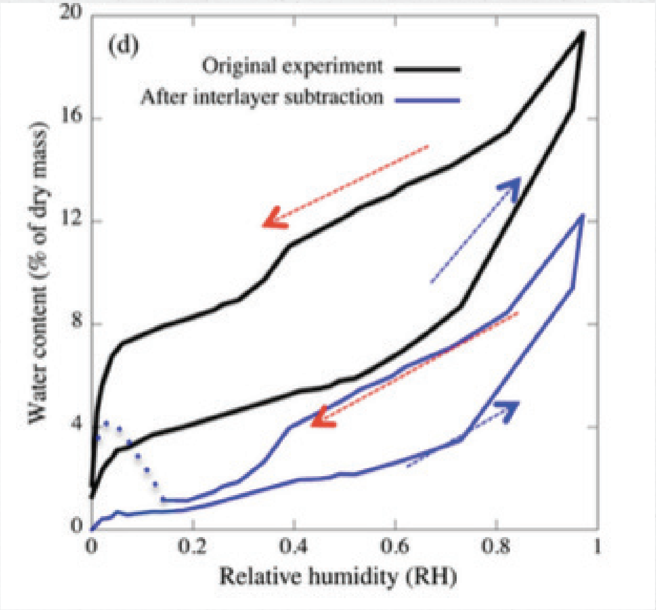
HYSTERESIS FROM MULTISCALE POROSITY

Pinson, M.B., Jennings, H.M., & Bazant, M.Z. (2014). Inferring Pore Size and Network Structure from Sorption Hysteresis. arXiv preprint arXiv:1402.3377.

A simple network-percolation model for the sorption hysteresis loop in the gel-pore network

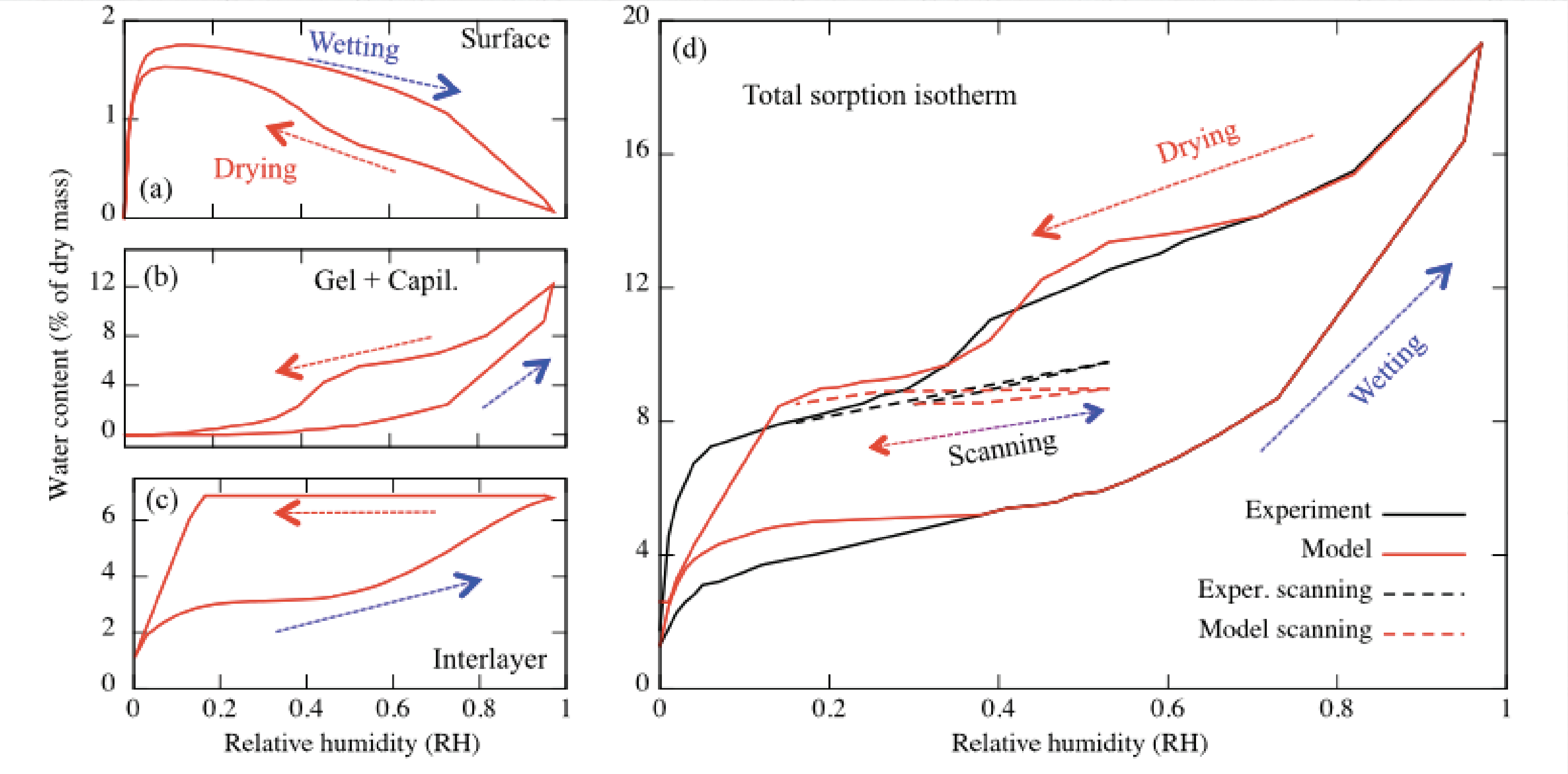
The "ink-bottle" effect dominates → Kelvin equation applied to adsorption
→ gel pore size distribution

Percolation model → network connectivity from the desorption path (a chain model with average connectivity 2 seems accurate)



- Simple models based on the Kelvin equation applied to a network of gel pores can fit the reduced isotherm for the gel-pore water, providing insight into the gel-pore structure topology (size distribution and connectivity)

HYSTERESIS FROM MULTISCALE POROSITY



- Summing together the interlayer isotherm, the fitted gel-pore isotherm, and a Langmuir gel-pore-surface adsorption curve, the total water sorption isotherm is captured.
- The surface hysteresis is a bi-product of the hysteresis in gel-water content

HYSTERESIS FROM MULTISCALE POROSITY

Total strain given by 3 additive contributions

Gel pores

Kelvin-Laplace theory

$$\varepsilon_L = \frac{1}{3}\frac{kT}{a^3}\ln(hS)\left[\frac{1}{K_b} - \frac{1}{K_s}\right]$$

Interlayer pores

Linear relation between water content and strain

$$\varepsilon_I = \frac{\lambda}{3} v_I,$$

Surface of gel pores

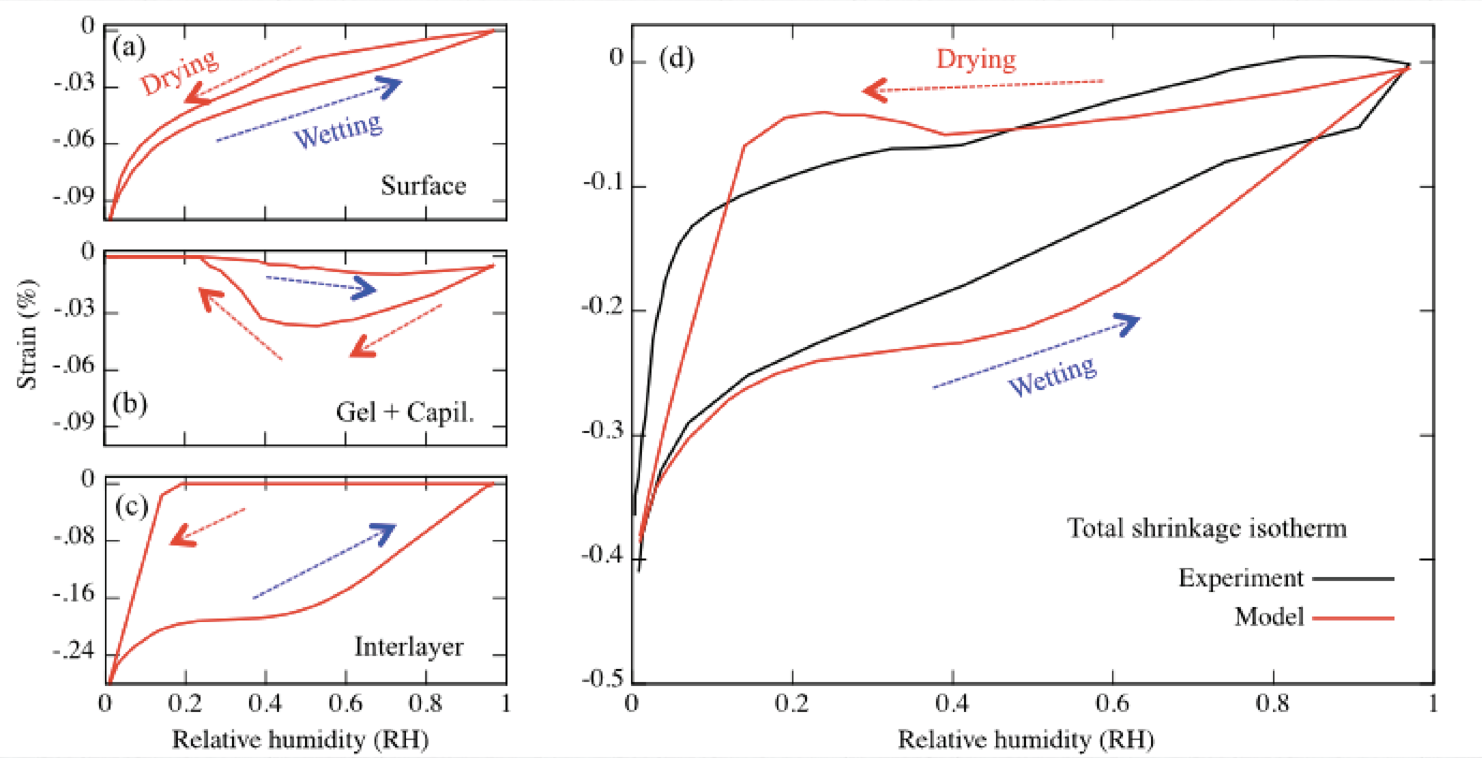
Bangham-Gibbs equation

$$\varepsilon_S = -\frac{\Delta(\sigma\gamma)}{3K(1-2\nu)},$$

$$\gamma = \gamma_0 - \frac{kT}{a^2}\int_{h_0}^{h}\theta\frac{dh}{h},$$

- Classical models account for the macroscopic strain due to gel-pore water
- The macroscopic strain due to interlayer water is heuristically related to the water content v_I via a proportionality constant λ, which turns out to be <<1. This is common in other microporous materials, e.g. coal

HYSTERESIS FROM MULTISCALE POROSITY



- Predicted hysteretic shrinkage isotherms of gel pores and their surfaces
- The interlayer shrinkage isotherm is given by the fitting parameter λ
- Open questions: What is the origin of λ? Can we model it instead via the disjoining pressure?

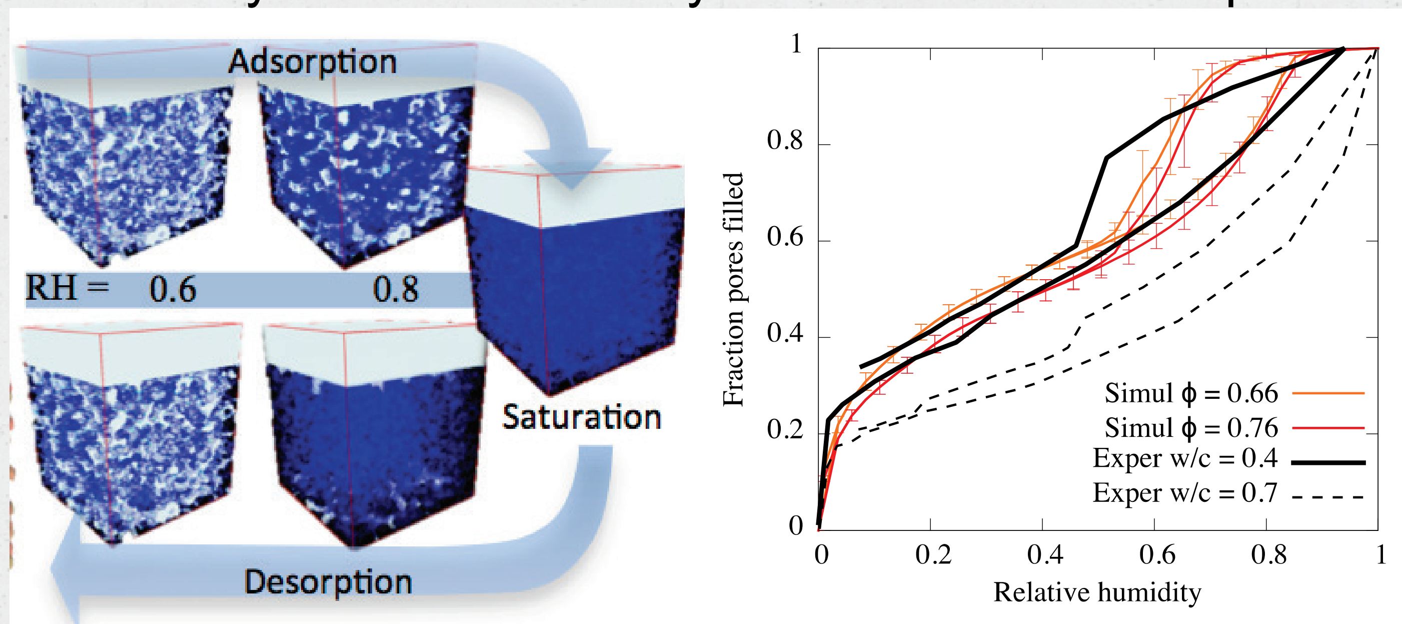
HYSTERESIS FROM MULTISCALE POROSITY

- Shrinkage hysteresis on mature pastes at 2+ drying cycles is due to sorption hysteresis (no creep, no plasticity)
- Sorption isotherms can provide unperturbed information on the pore structure of a cement paste
- We can separate the water-pore interaction in interlayer spaces (< 1nm) and gel pores (1-100 nm)
- If the paste is never dried below 25% RH, we can neglect the interlayer spaces

- Our heuristic treatment of interlayer water needs theoretical backups: disjoining pressure? Layer collapse? → back to fundamental modelling

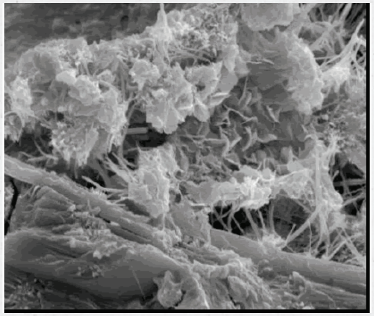
WHERE BOTTOM-UP AND TOP-DOWN MEET

Density Functional Theory simulations of N2 sorption



- Model C-S-H mesostructures provide a basis to simulate sorption
- Gel-adsorbed water, plus humidity-dependent particle shape, plus humidity-dependent interactions between particles → simulated shrinkage to shed light onto the propagation of strain from the interlayer to meso scale

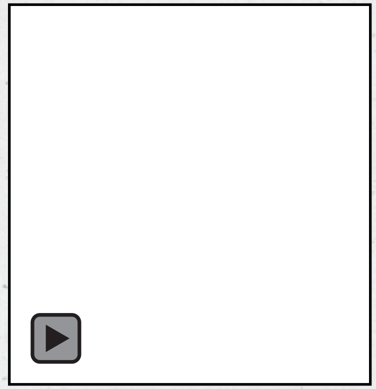
WHERE BOTTOM-UP AND TOP-DOWN MEET

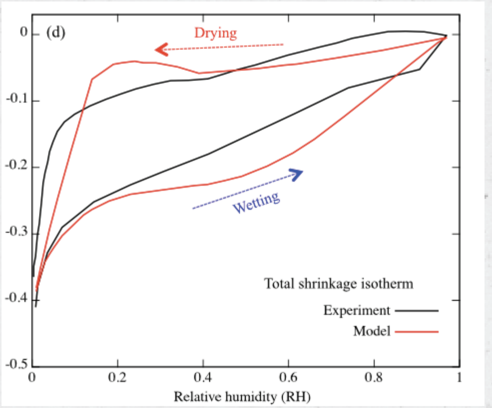


Processing

Structure

Properties





- Including processing (formation) and ageing in multiscale modelling provides new opportunies for industrial applicability: from naostructure-properties paradigm to processing-properties paradigm, mediated by the nanostructure

TU 1404
COST ACTION

Back to the list of presentations

TU1404 COST ACTION

Homogenization approach for description of concrete viscoelasticity

Julien Sanahuja et al. – EDF lab, France

EDF

Homogenization approach for description of concrete viscoelasticity

Micromechanics: a useful tool to investigate cementitious materials

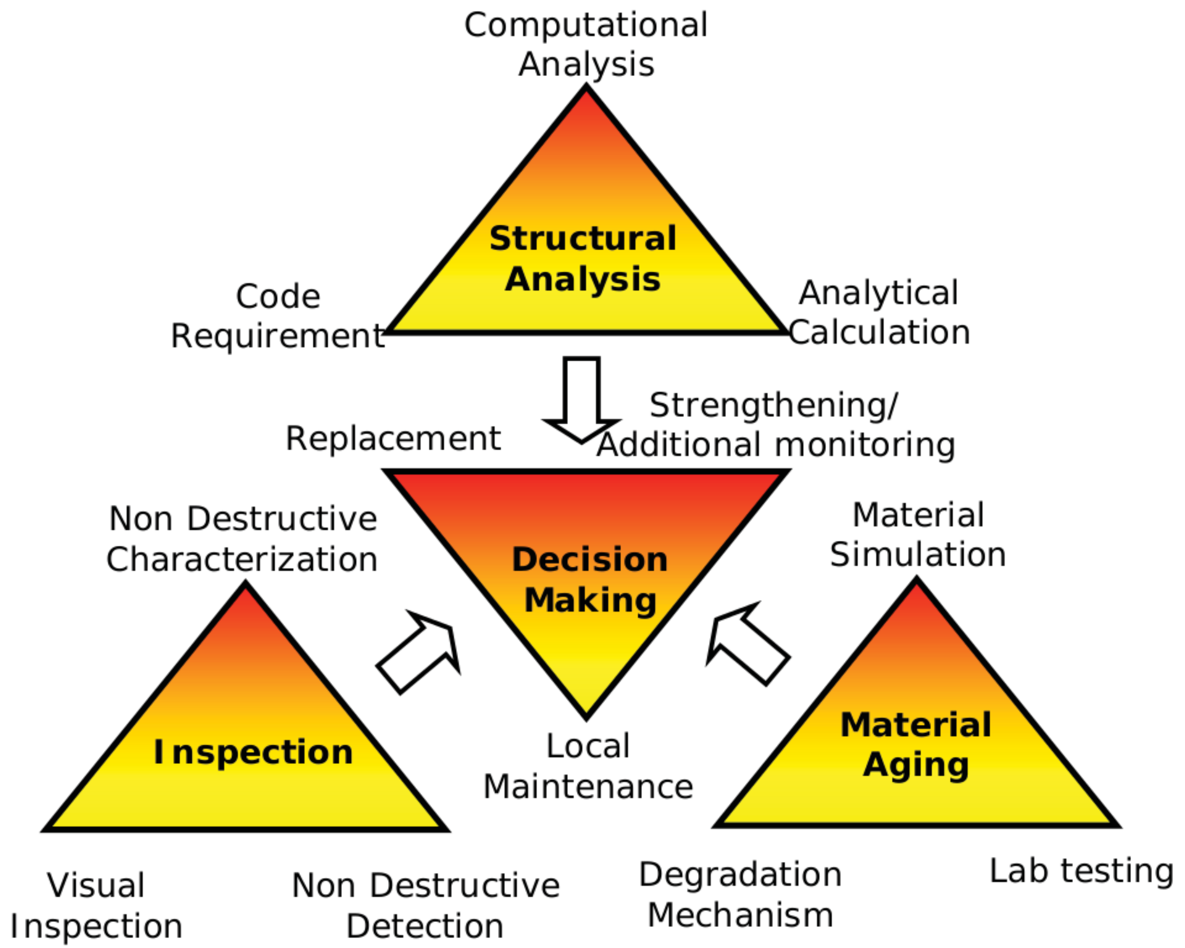
Julien SANAHUJA et al.

EDF lab

COST ACTION TU1404 – 20 september 2015

Long term operation of civil engineering structures

At EDF



3 pillars: inspection, structural analysis, material ageing

Material behaviour: needs and specific aspects

Structure computations

- behaviour laws specific to the concrete(s) of this structure

Inspection

- link between indirect measurement and usable property?
- requires knowledge on the behaviour of the material

$\Rightarrow$ Needs

(Extracted) samples or formulation $\Rightarrow$ (long term) behaviour

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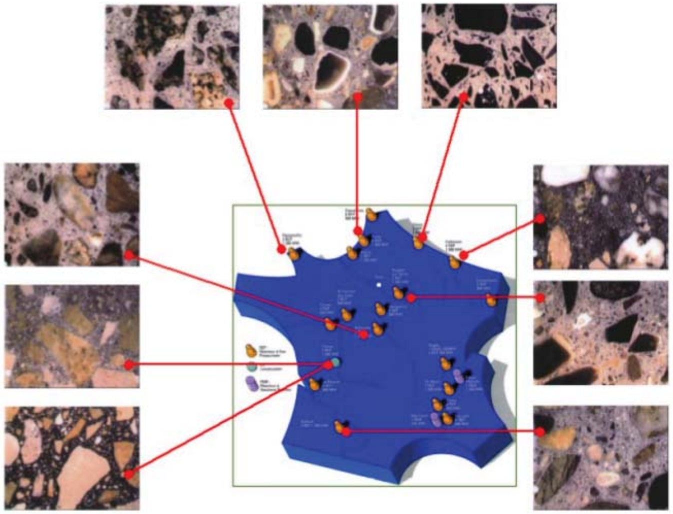

Specificities of concrete material

- multi-scale
- multi-physics
- interacts with water
- interacts with environment
- huge variability

Need to go beyond the empirical approach

"Gel-space ratio" = $V_h/(V_h + V_{cap}) \Rightarrow R_c$

too restrictive today [P. TERMKHAJORNKIT et al., CCR, 2014]

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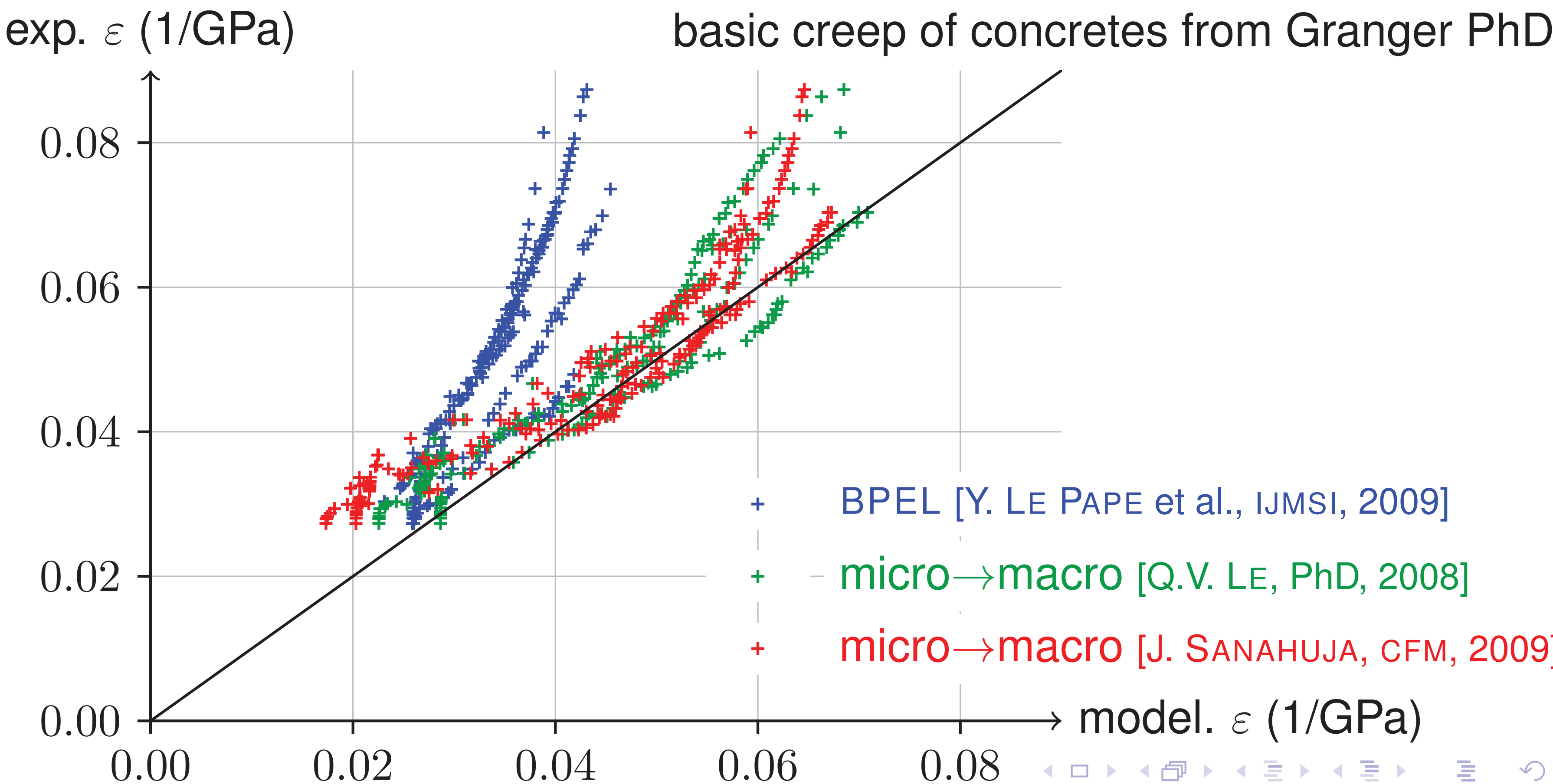
Better microstructure and physics ⇒ what kind of improvement?



1. Morphological model of paste: design and validation wrt. elasticity
   - Morphology: observations and modelling
   - Validation
   - Does shape matter?
2. Non ageing viscoelasticity
   - Creep micro-mechanism considered
   - C-S-H gel
   - Cement paste
3. Ageing viscoelasticity
   - Micromechanical extension of Bažant solidification theory
   - Application to model porous materials
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Outline

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Observation of C-S-H precipitation

S. GARRAULT-GAUFFINET, 1998

AFM observation of a C_3S crystal covered by a lime-saturated droplet

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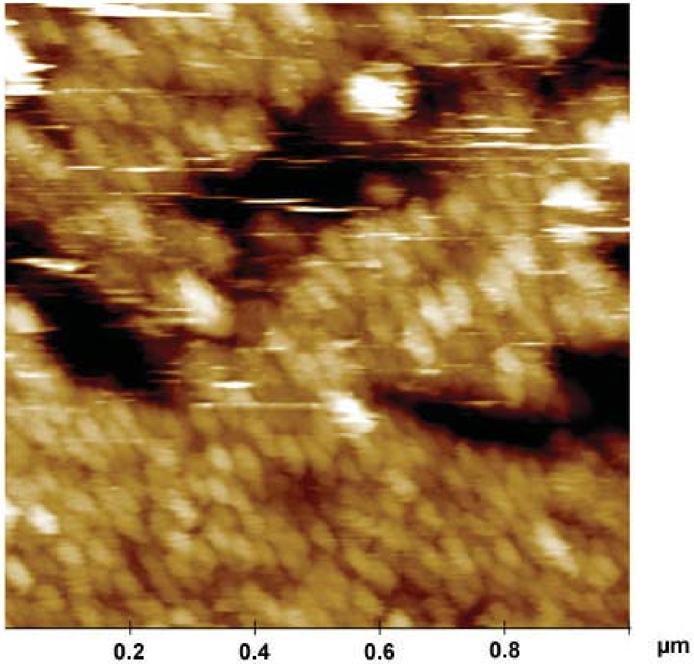

Small particules of C-S-H, anisotropic shape

- parallel to the grain surface
  60 nm by 30 nm
- thickness: 5 nm

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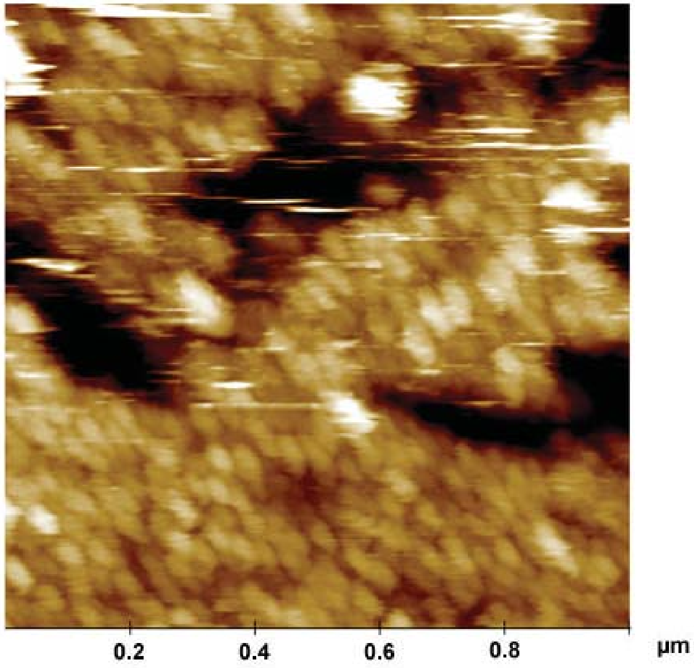

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⇒ elementary bricks of C-S-H

$r_s = 5/\sqrt{30 * 60} \approx 0.12$

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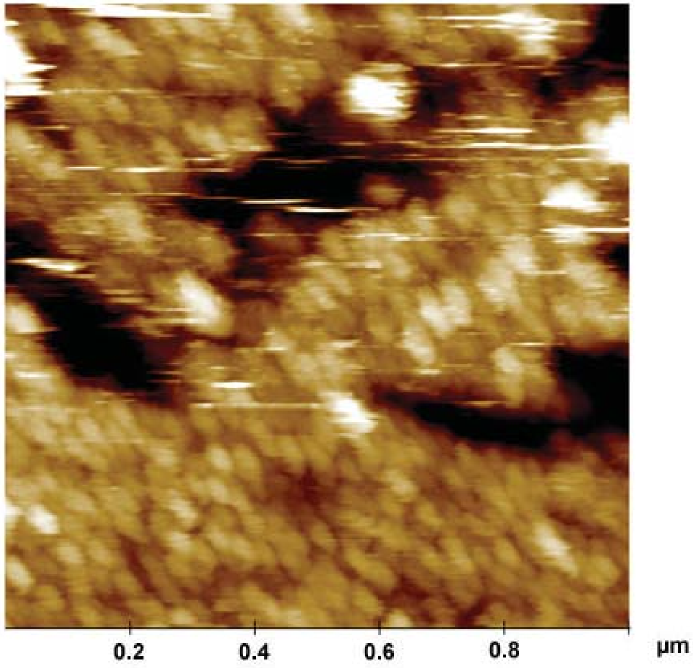

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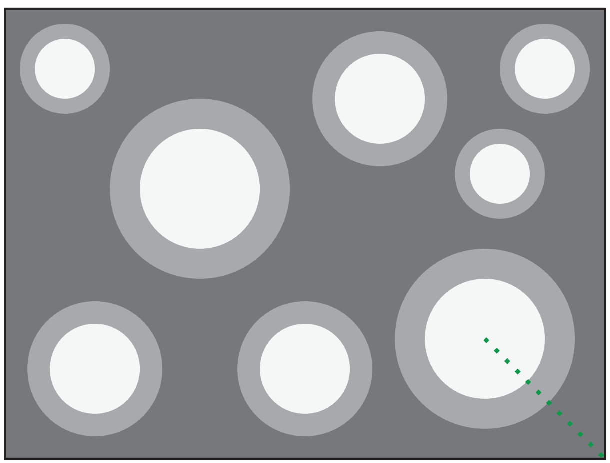
⇒ elementary bricks of C-S-H

$$r_s = 5/\sqrt{30 * 60} \approx 0.12$$

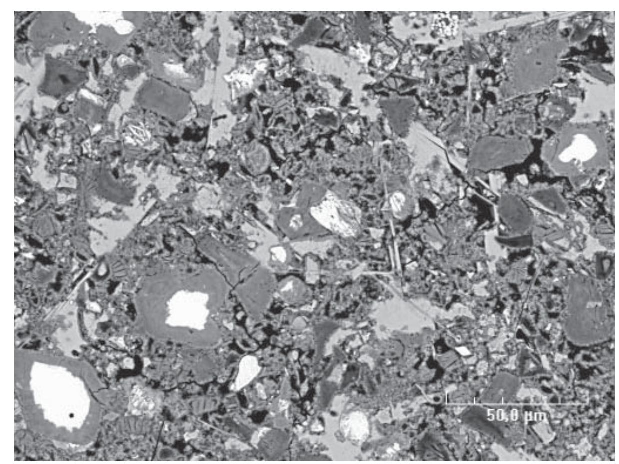
Question of the morphology of C-S-H still widely opened

we chose a representation based upon these elementary bricks

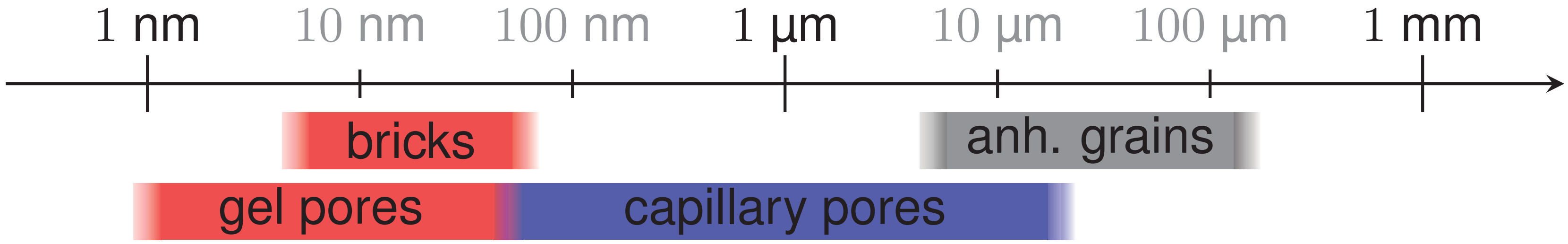
Morphological model

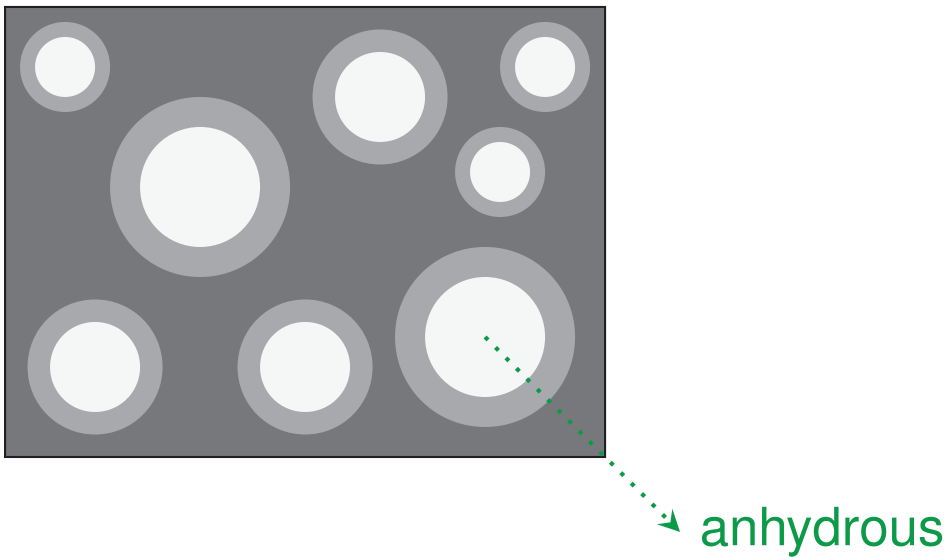


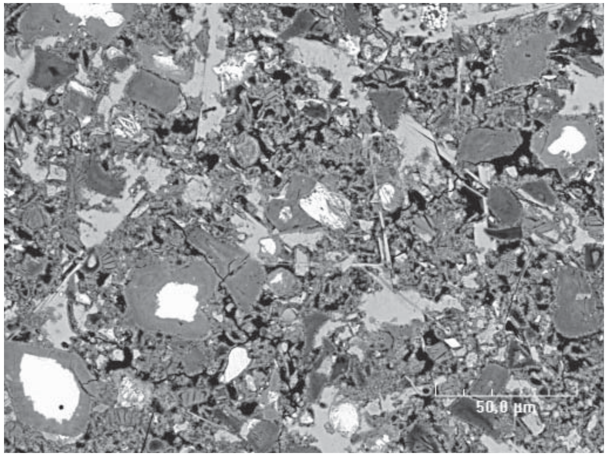
anhydrous



Morphological model







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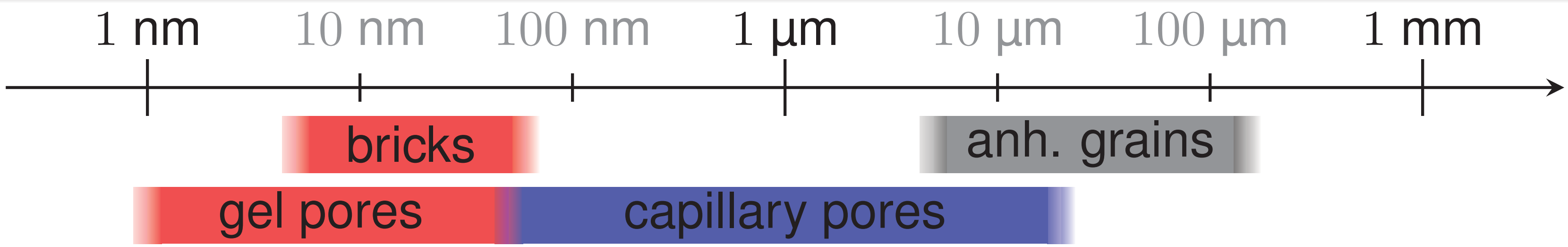

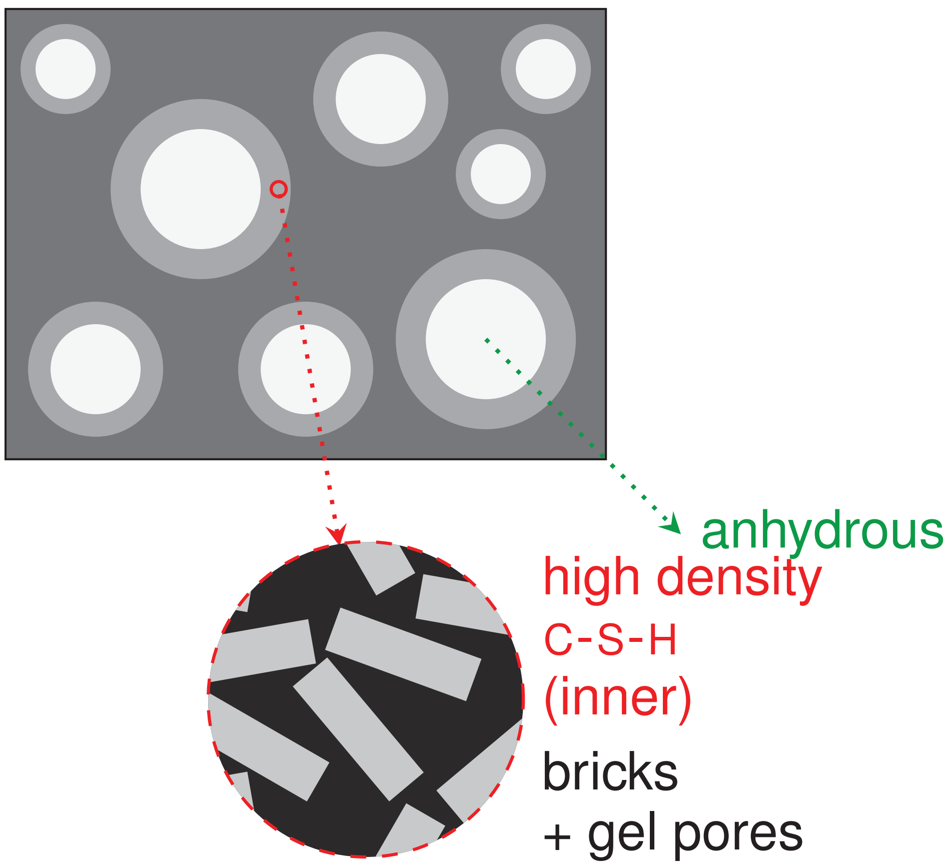

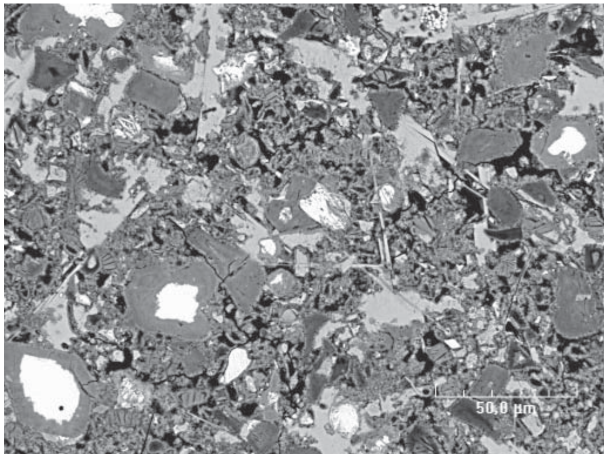

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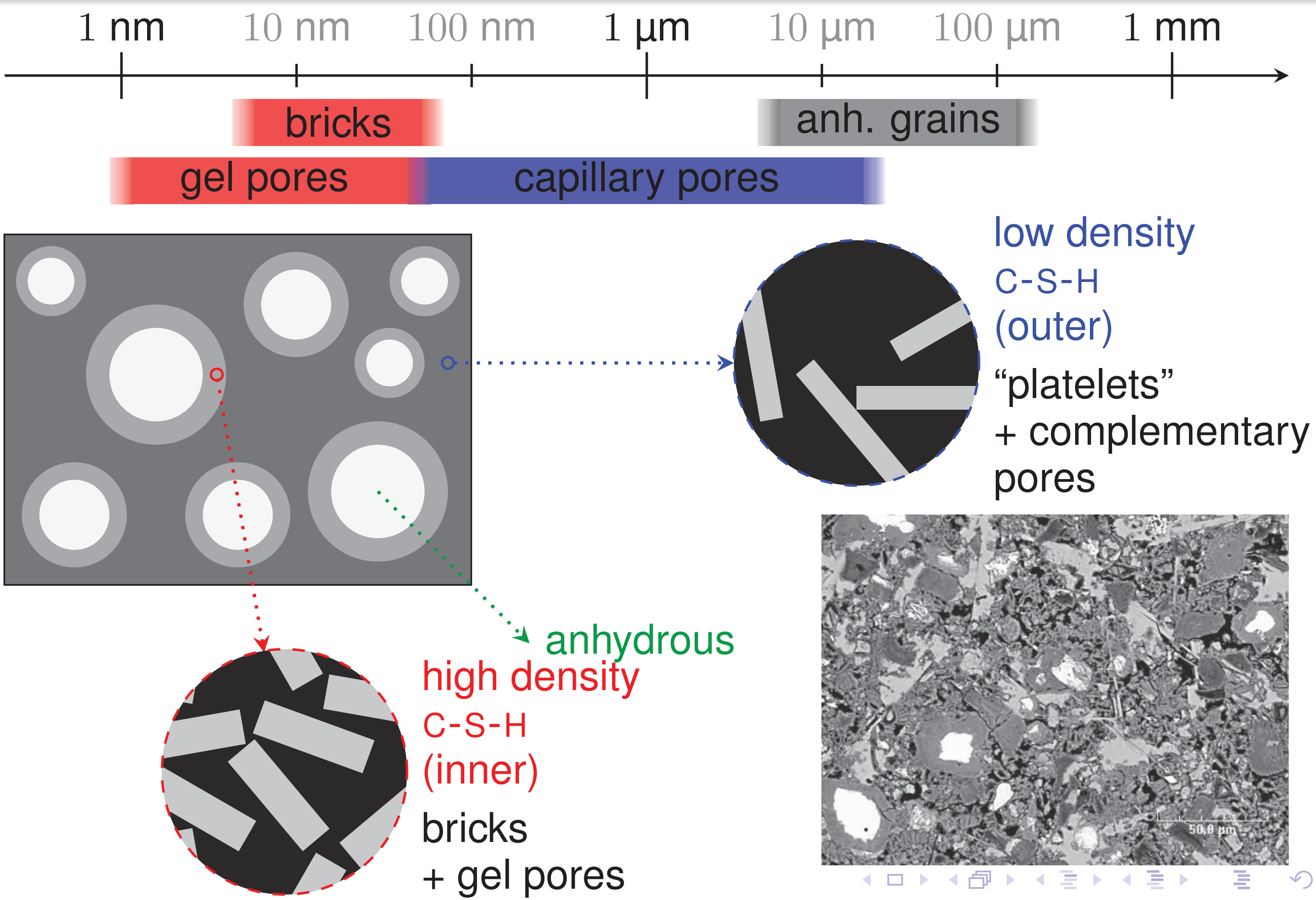
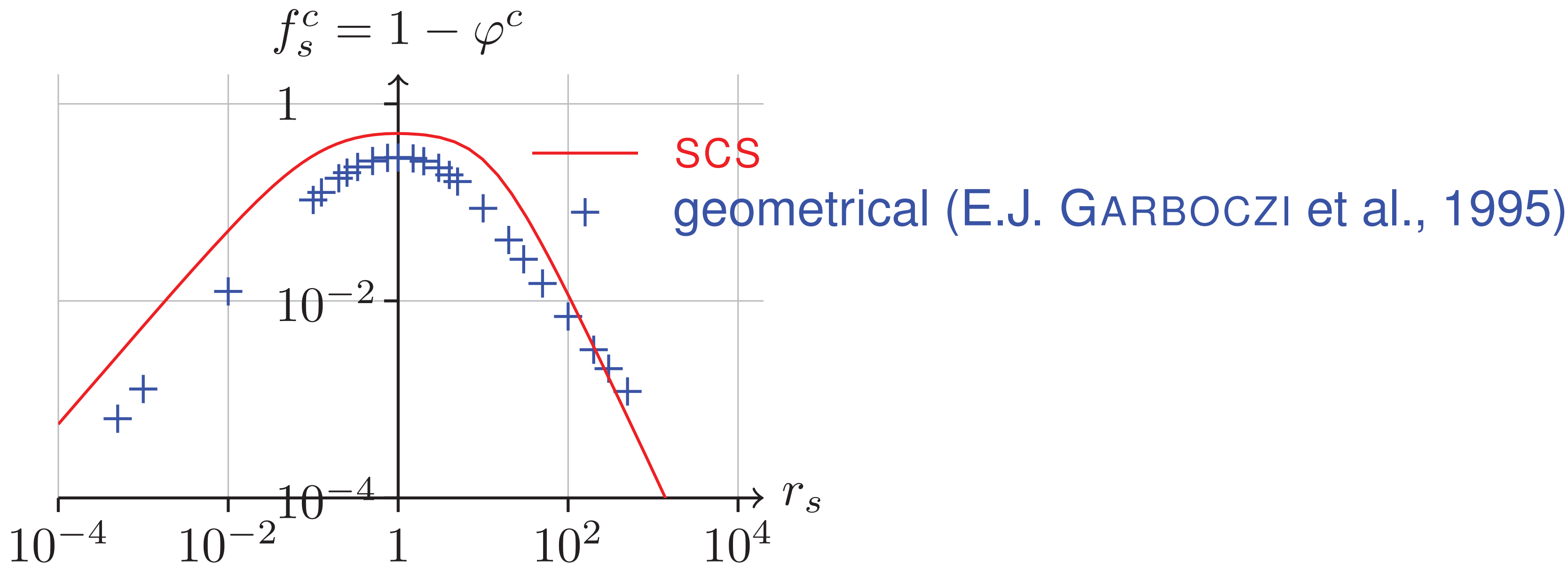
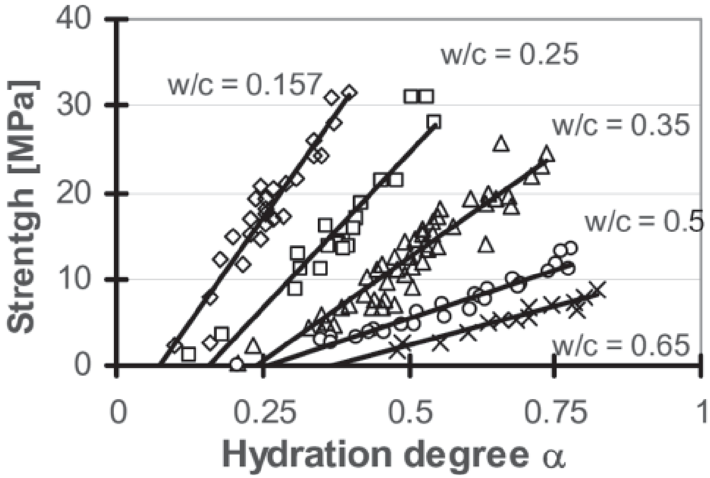


Aspect ratio of platelets calibrated on setting data



Aspect ratio of platelets calibrated on setting data

Setting degree of hydration estimated
(J.M. TORRENTI et al., 2005)
on compressive strength tests
(J. BYFORS, 1980)



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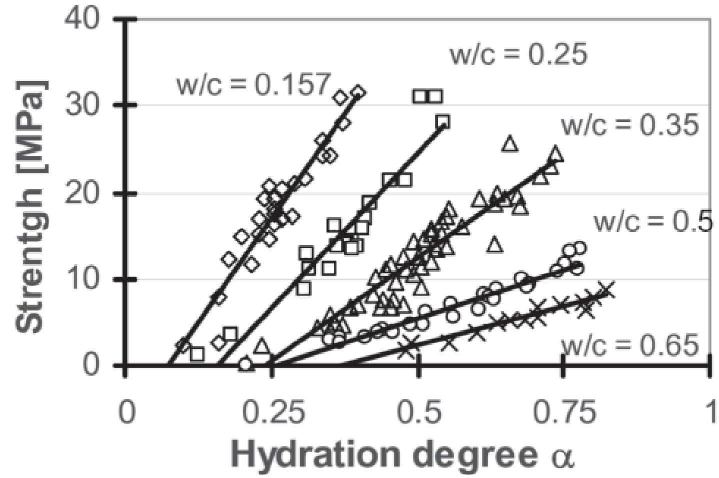

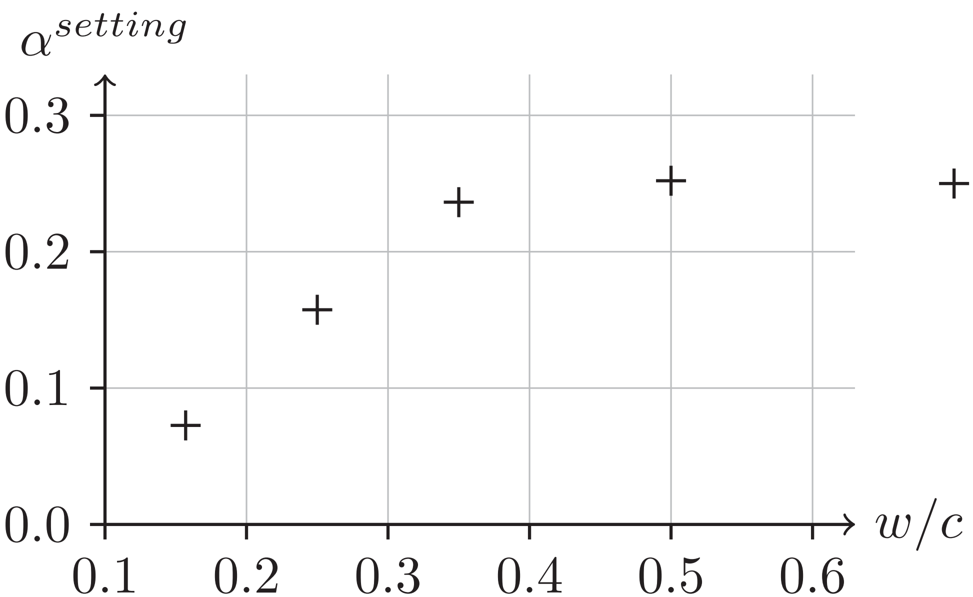

+ exp. estimation

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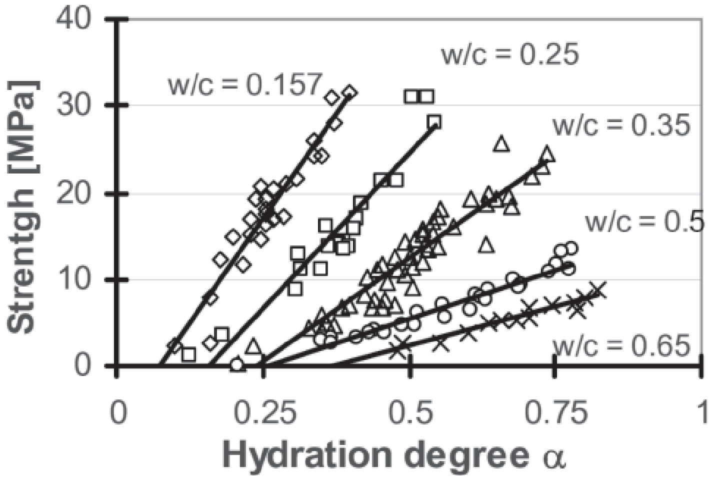

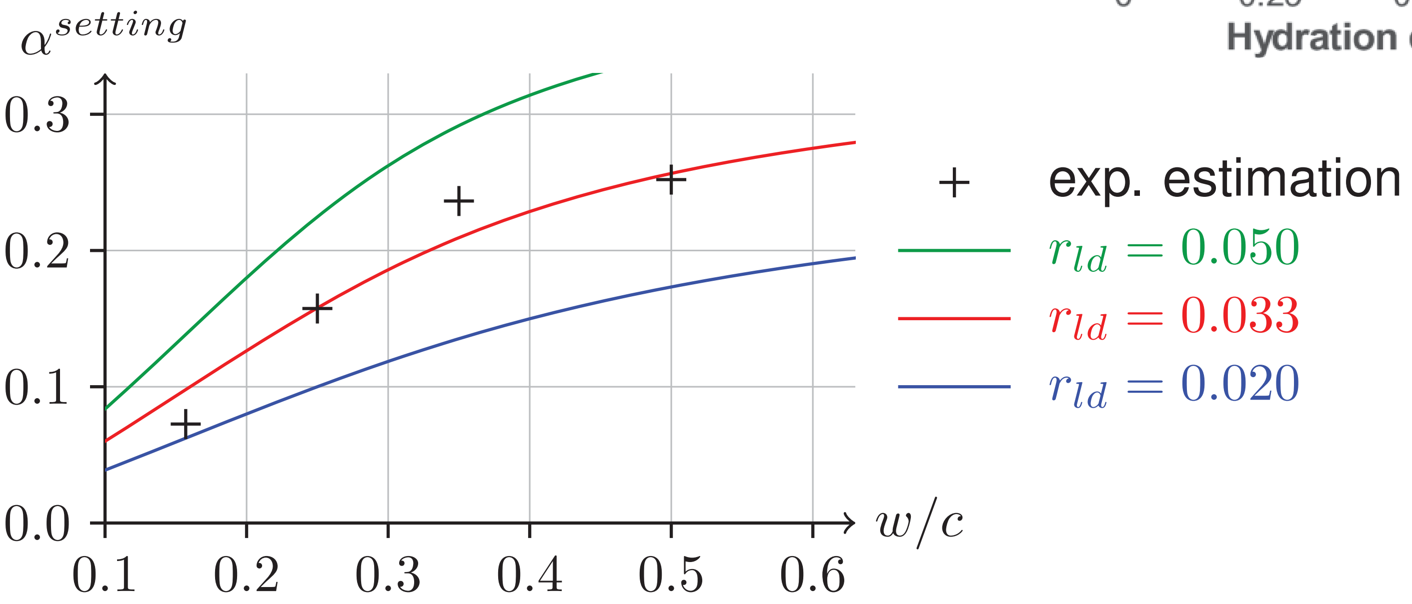

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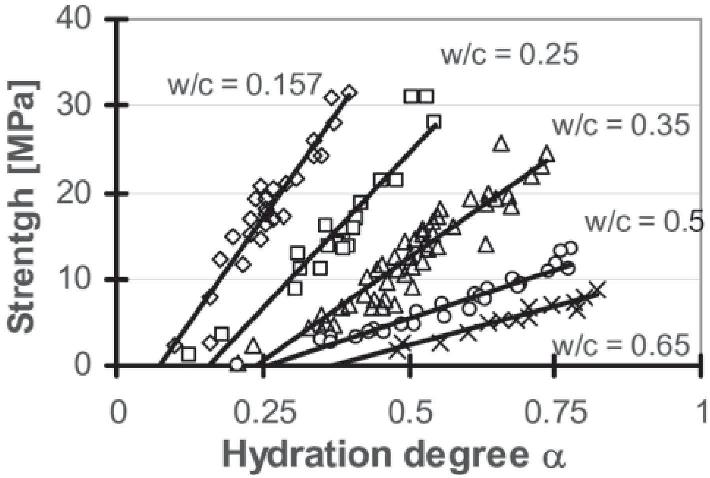
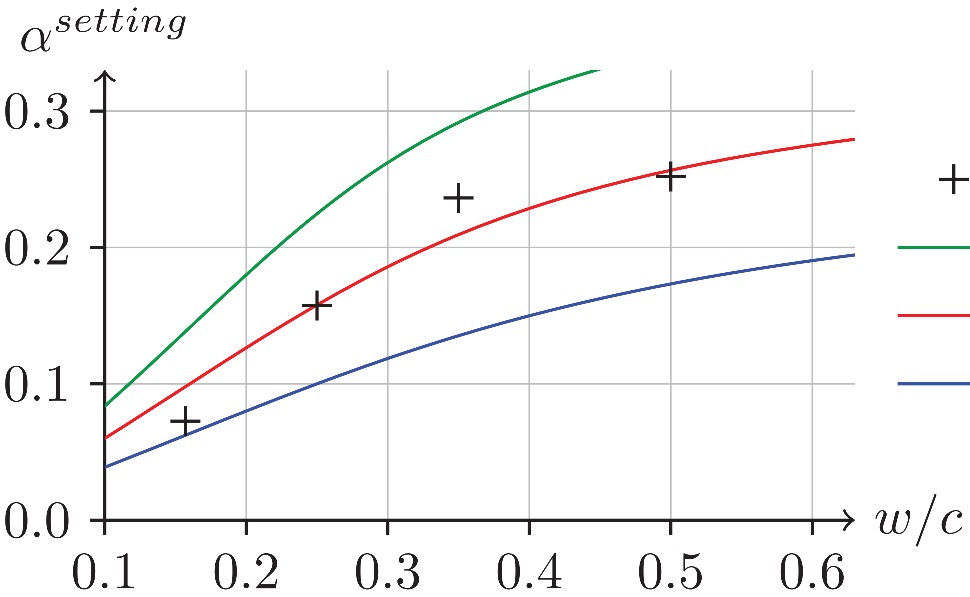
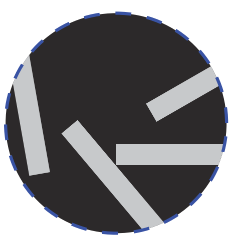
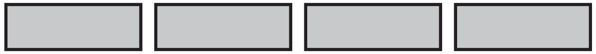




+ exp. estimation
$r_{ld} = 0.050$
$r_{ld} = 0.033$
$r_{ld} = 0.020$

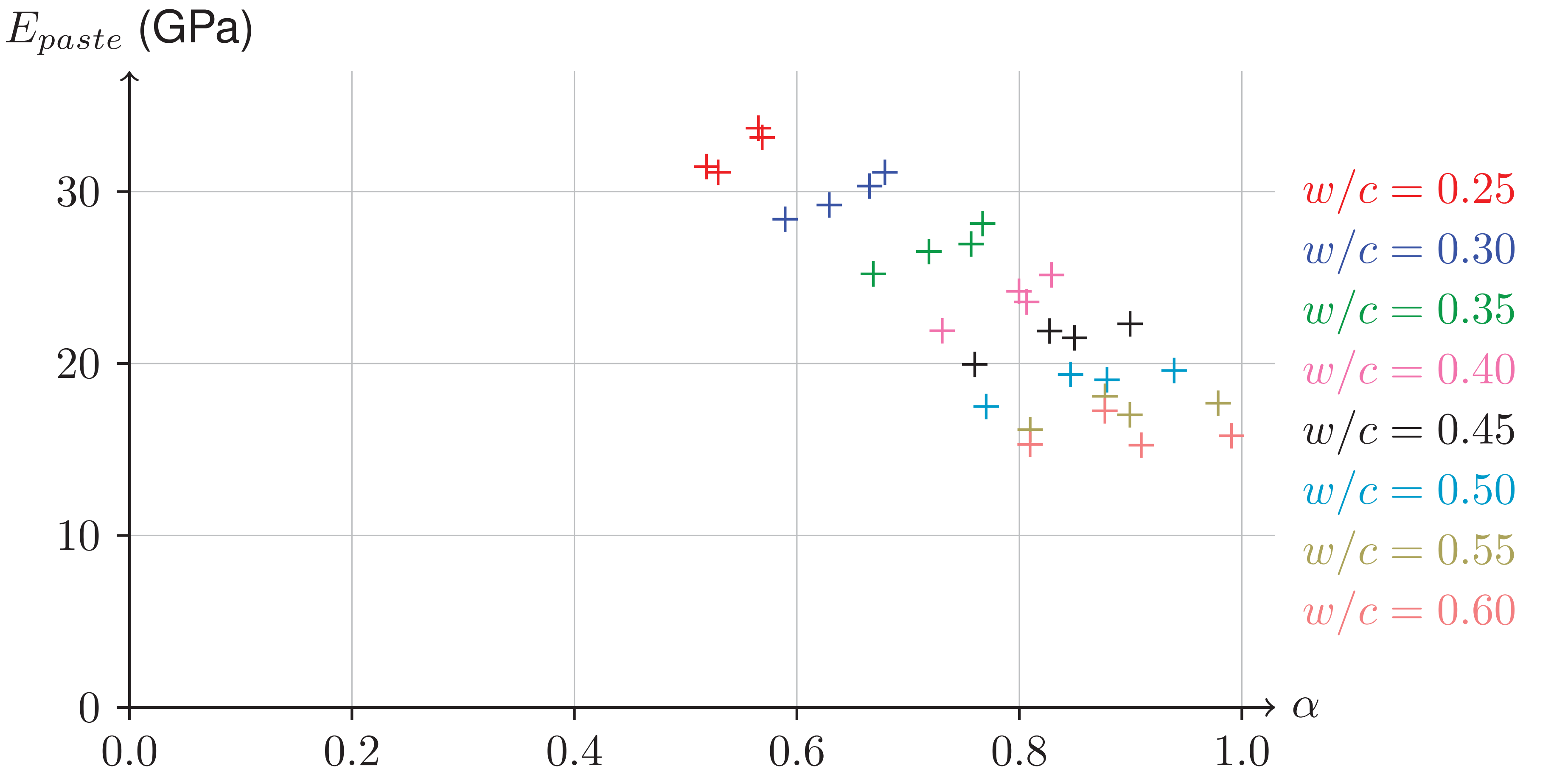


we keep $r_{ld} = 0.033 \approx r_{hd}/4$



Young's modulus during hydration

experimental data: C.-J. HAECKER et al., 2005



[J. SANAHUJA, L. DORMIEUX, G. CHANVILLARD. *Modelling elasticity of a hydrating cement paste.* CCR 37 (2007)]

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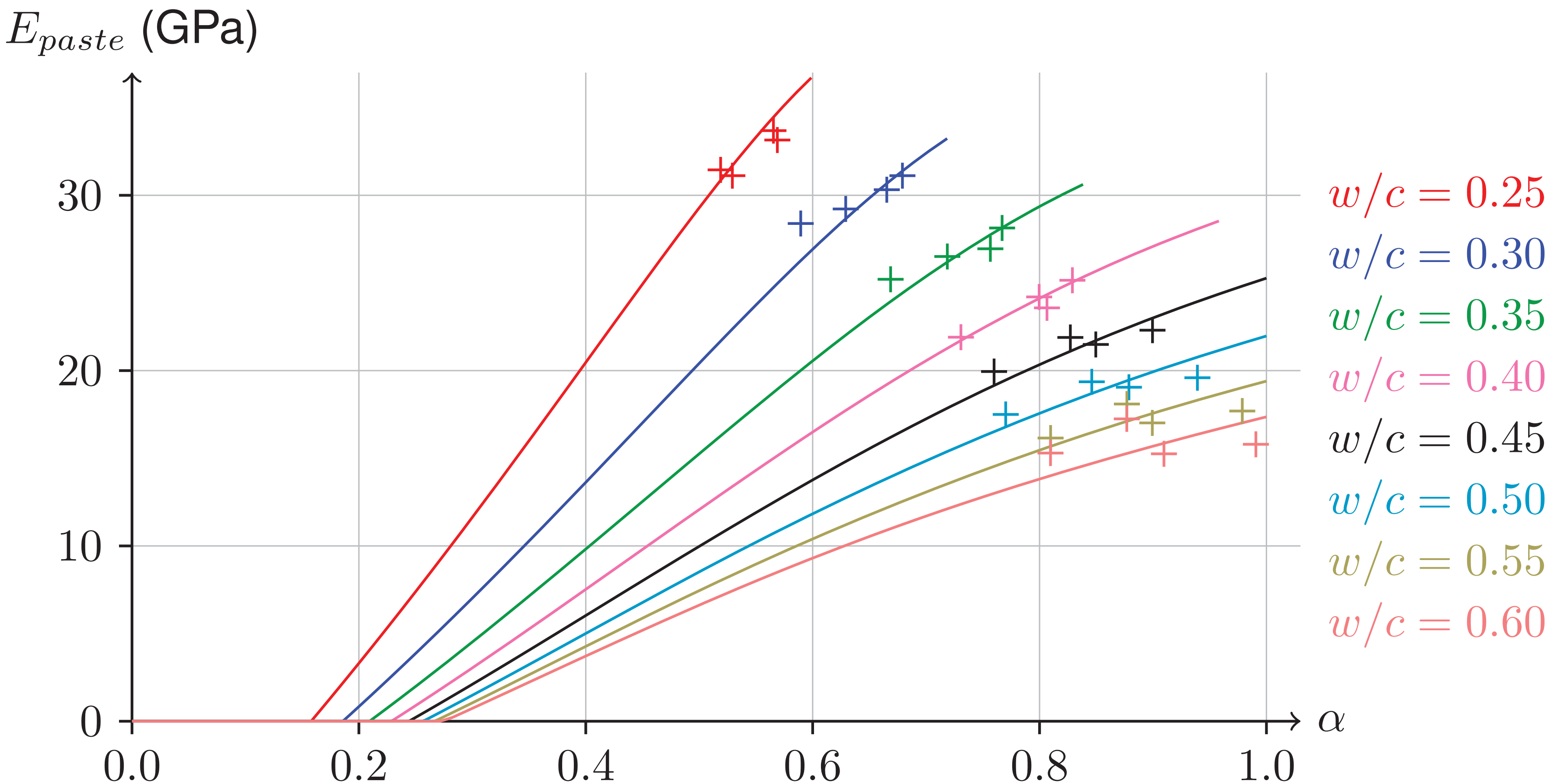

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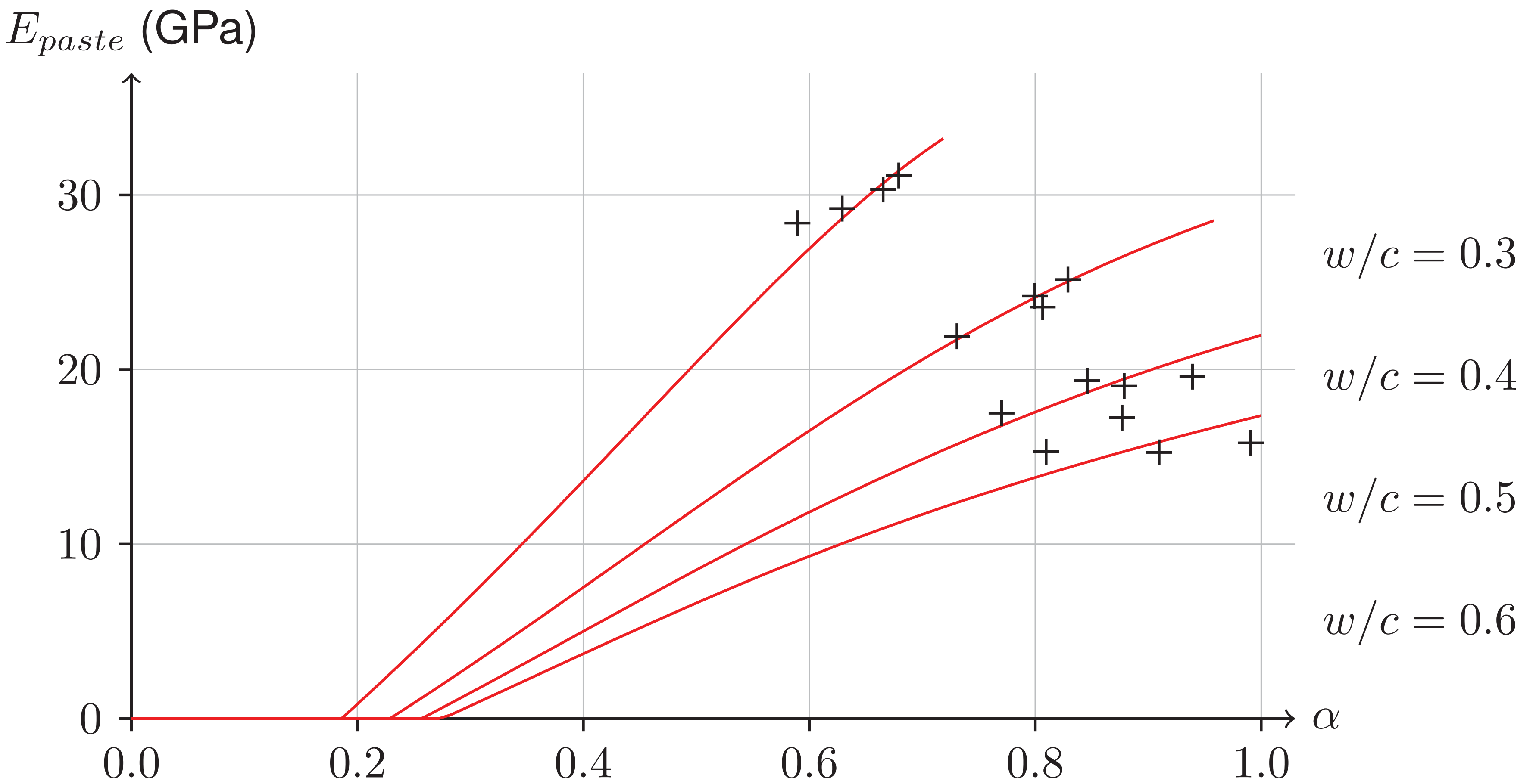
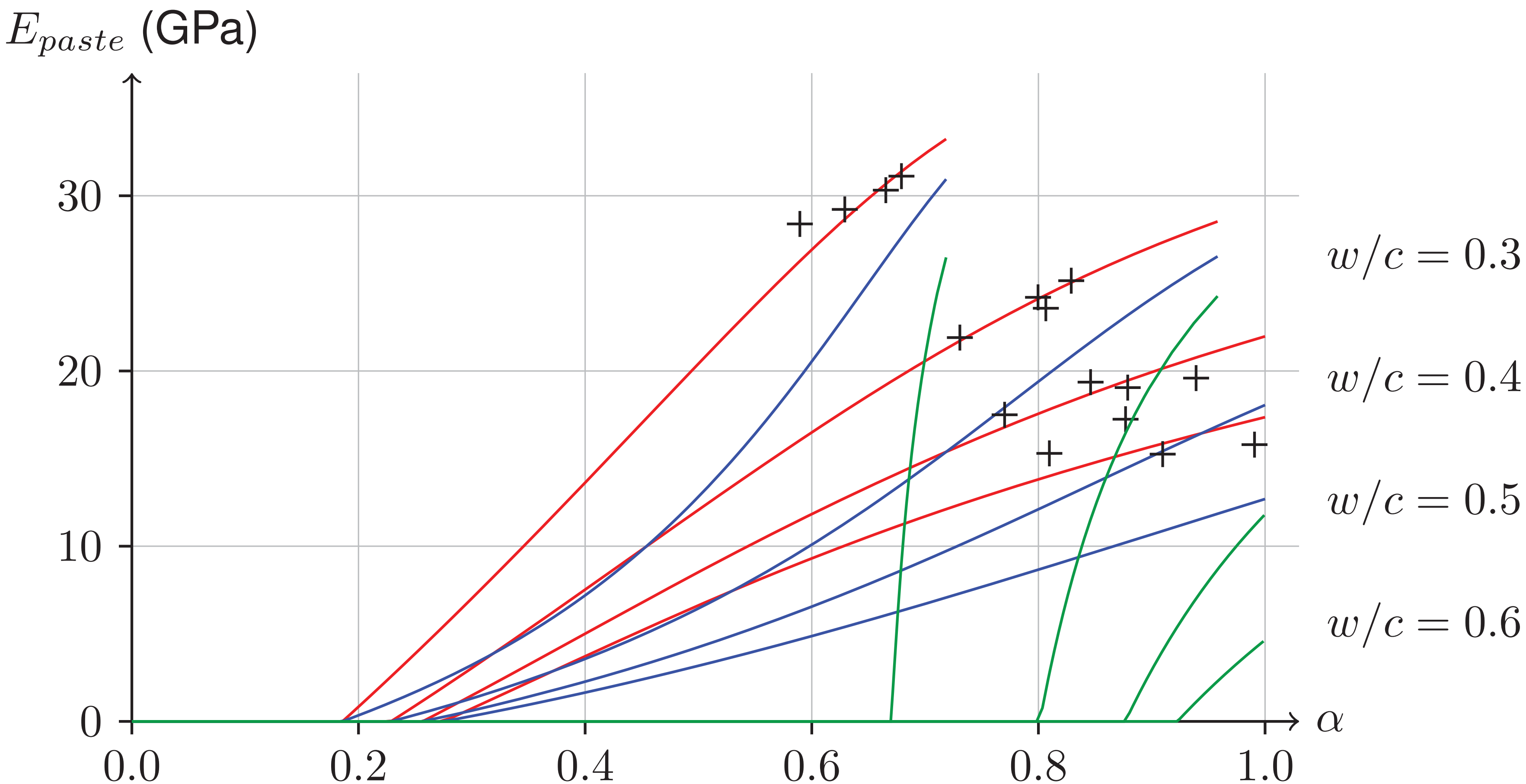
Influence of the shape of the LD solid particles?

platelets: $r_{ld} = 0.033$



Influence of the shape of the LD solid particles?

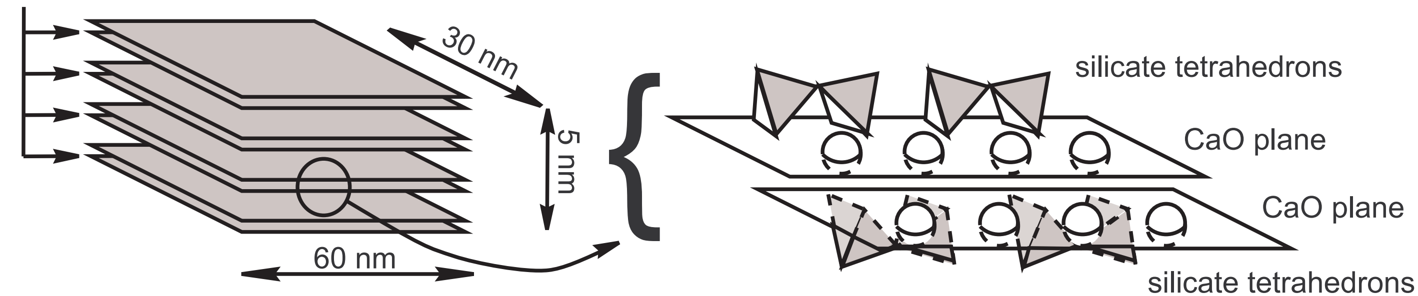
platelets: $r_{ld} = 0.033$ needles: $r_{ld} = 19$ spheres: $r_{ld} = 1$



Outline

Sheets: viscous sliding

C-S-H elementary bricks: sheet stack model



(R. Barbarulo, 2002
from A. Nonat, A.-C. Courault and D. Damidot, 2001)

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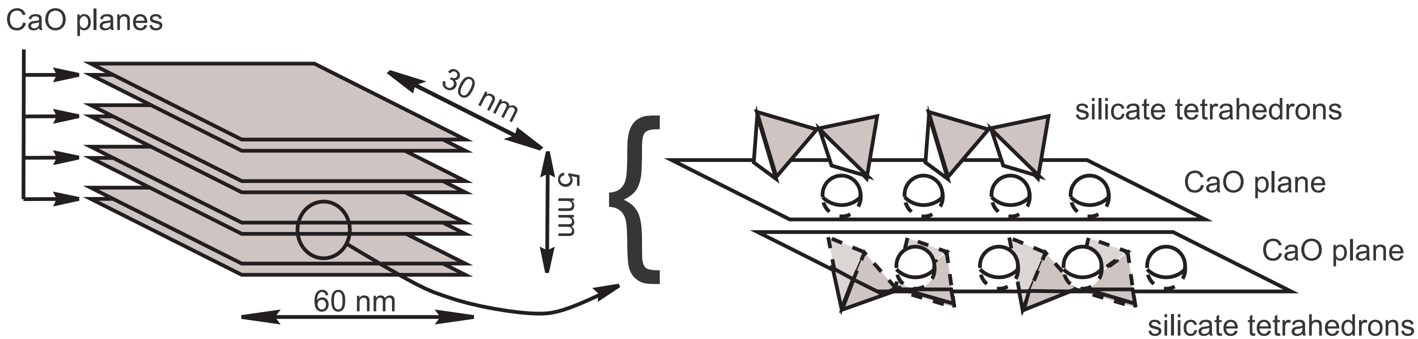

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Local mechanism? ⇒ creep observed at the macroscopic scale

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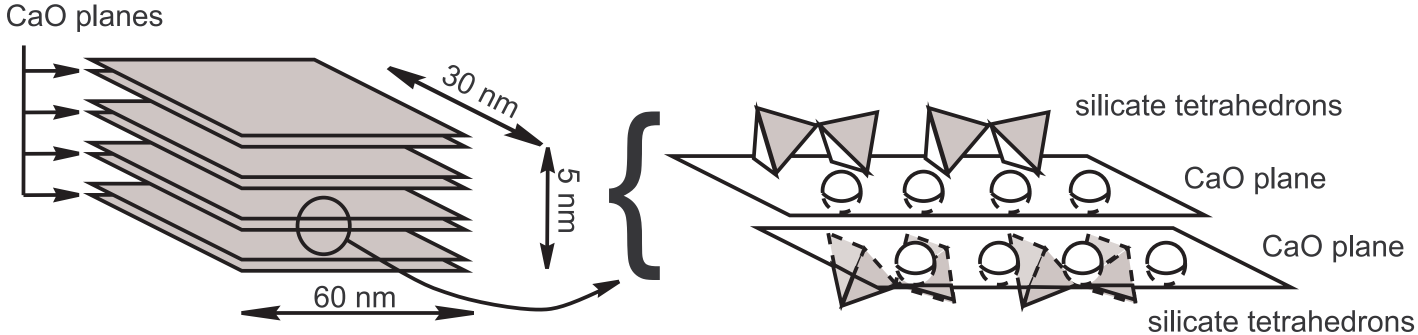

(R. Barbarulo, 2002
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Local mechanism? ⇒ creep observed at the macroscopic scale

Hypothesis still in debate but suggested by many authors:
sliding of sheets

(R.P. Lohtia, 1970)
(B.T. Tamtsia and J.J. Beaudoin, 2000)
(F. Benboudjema, 2002)

Modifying the behaviour of the C-S-H particles

- viscoelastic shear, sheet onto sheet
- simple rheological model
- including the elastic model ($\rightarrow$ initial strain)

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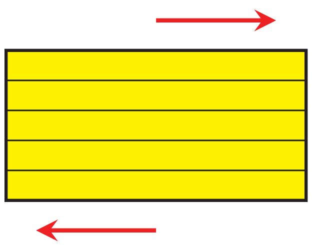

modifying the behaviour of the particle,
only for simple shear sheet onto sheet

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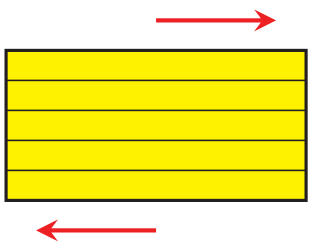

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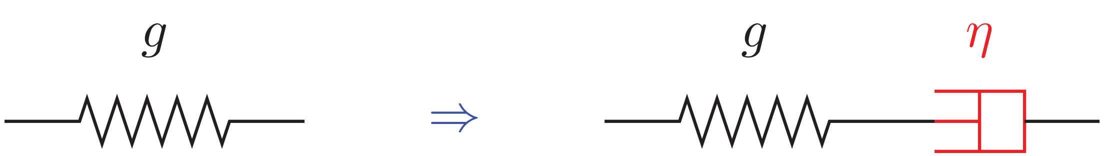

elasticity

viscoelasticity (Maxwell model)

$$\tau = \eta / g$$

Modifying the behaviour of the C-S-H particles

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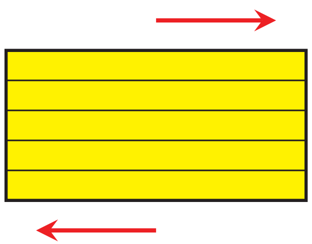
- including the elastic model ($\rightarrow$ initial strain)



modifying the behaviour of the particle,
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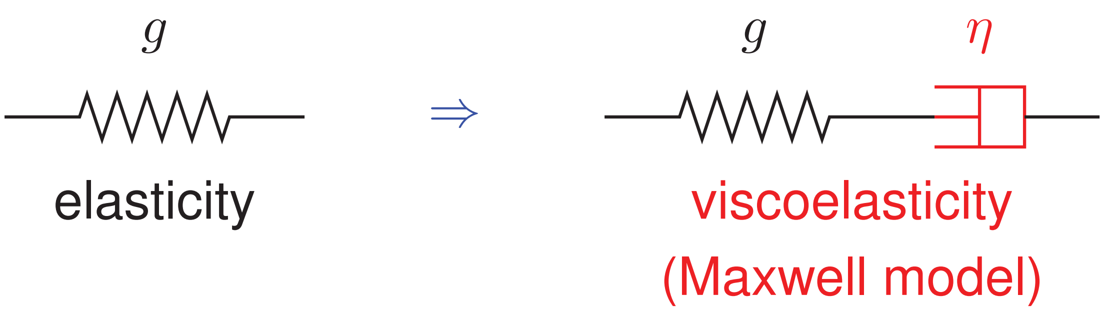
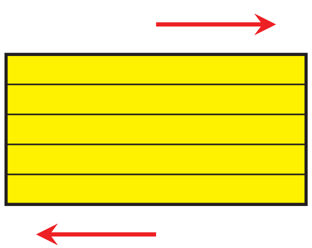


$\tau = \eta / g$

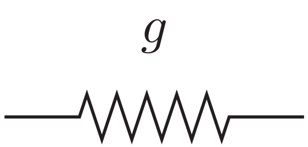
other strain mechanisms: isotropic elastic behaviour (k, g)

Modifying the behaviour of the C-S-H particles

- viscoelastic shear, sheet onto sheet
- simple rheological model
- including the elastic model (→ initial strain)



modifying the behaviour of the particle, only for simple shear sheet onto sheet



elasticity

$\Rightarrow$

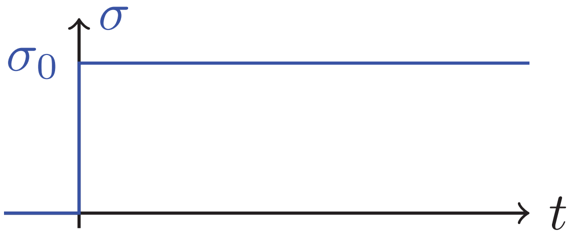
viscoelasticity (Maxwell model)

$\tau = \eta / g$

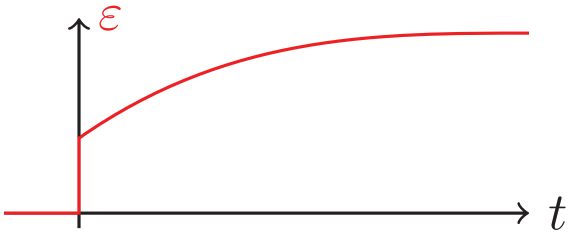
other strain mechanisms: isotropic elastic behaviour (k, g)

we consider the creep of a packing of such particles (with $r_s = r_{hd} = 0.12$)

Short-term creep ($t \ll \tau$)



$\Rightarrow$



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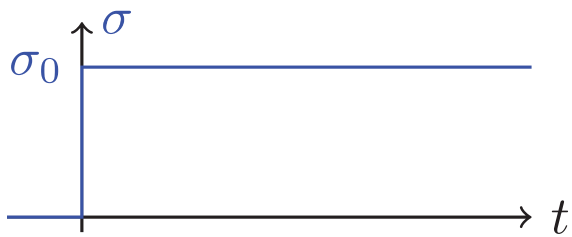
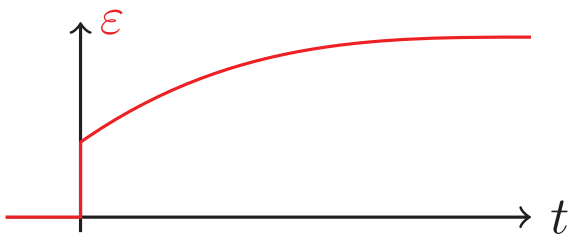
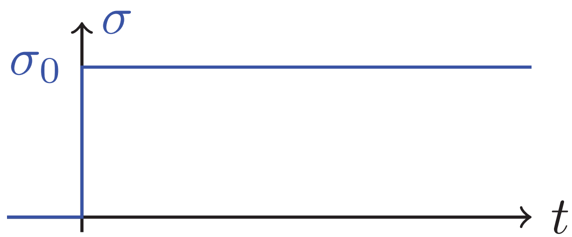


$\Rightarrow$

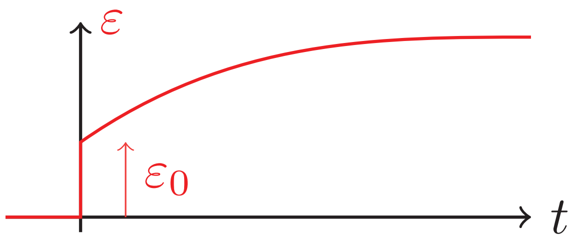


$$t^a = t/\tau \quad , \quad \varepsilon^a_{sph} = \frac{\varepsilon_{sph}}{\sigma_0/k} \quad \text{and} \quad \varepsilon^a_{dev} = \frac{\varepsilon_{dev}}{\sigma_0/k}$$

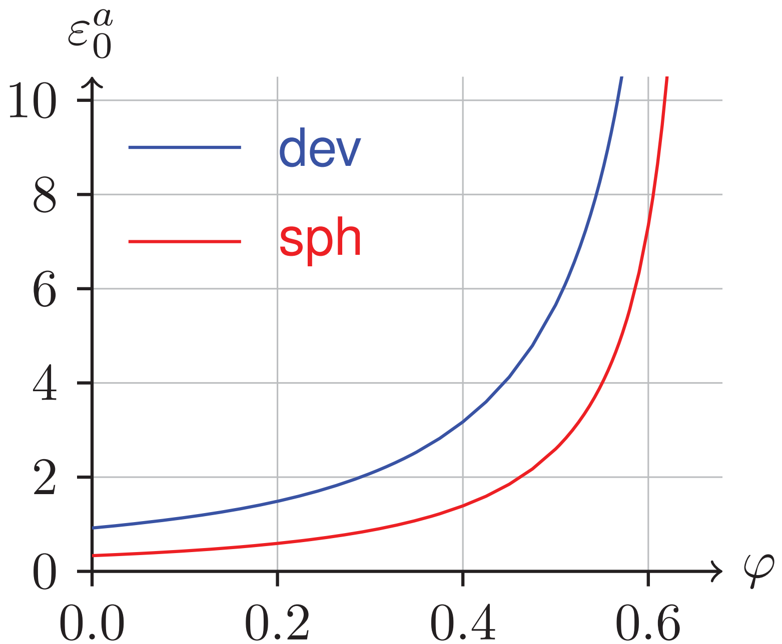
Short-term creep ($t \ll \tau$)



$\Rightarrow$

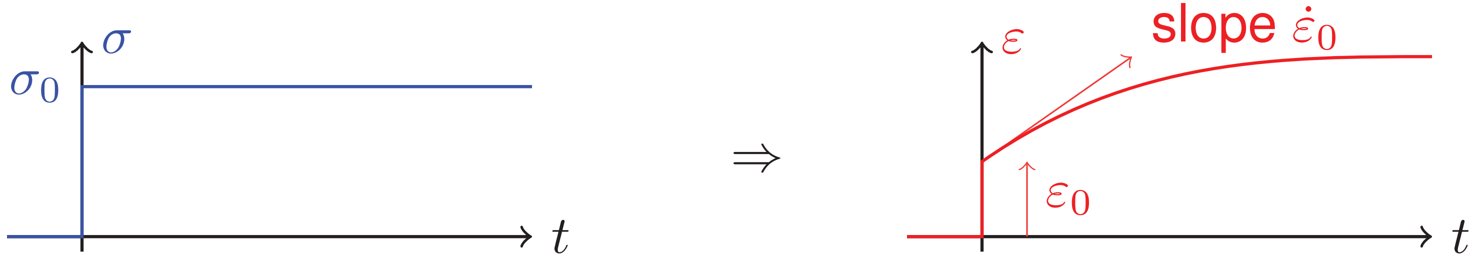


$t^a = t/\tau$, $\varepsilon^a_{sph} = \dfrac{\varepsilon_{sph}}{\sigma_0/k}$ and $\varepsilon^a_{dev} = \dfrac{\varepsilon_{dev}}{\sigma_0/k}$



$r_{hd} = 0.12 \Rightarrow$ threshold $\varphi^c = 0.67$

Short-term creep ($t \ll \tau$)



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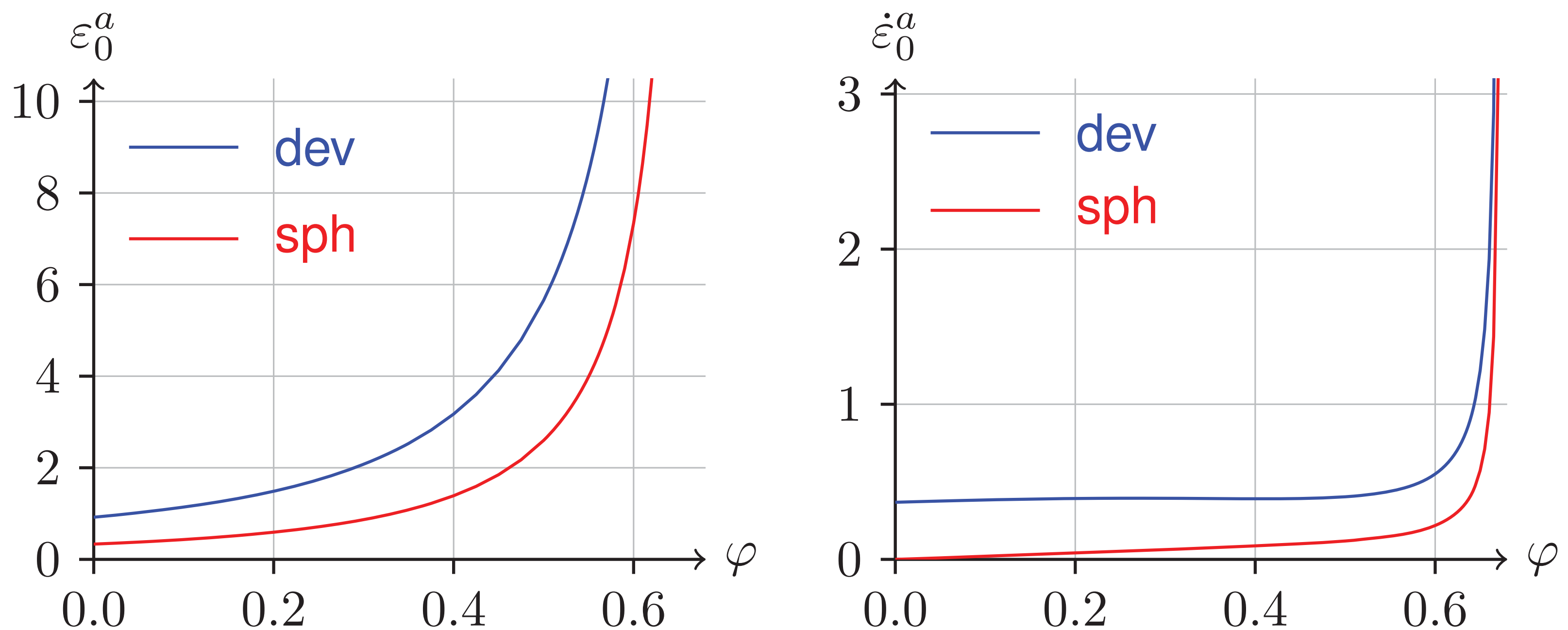
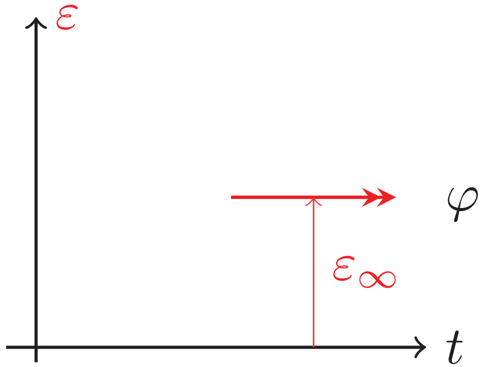
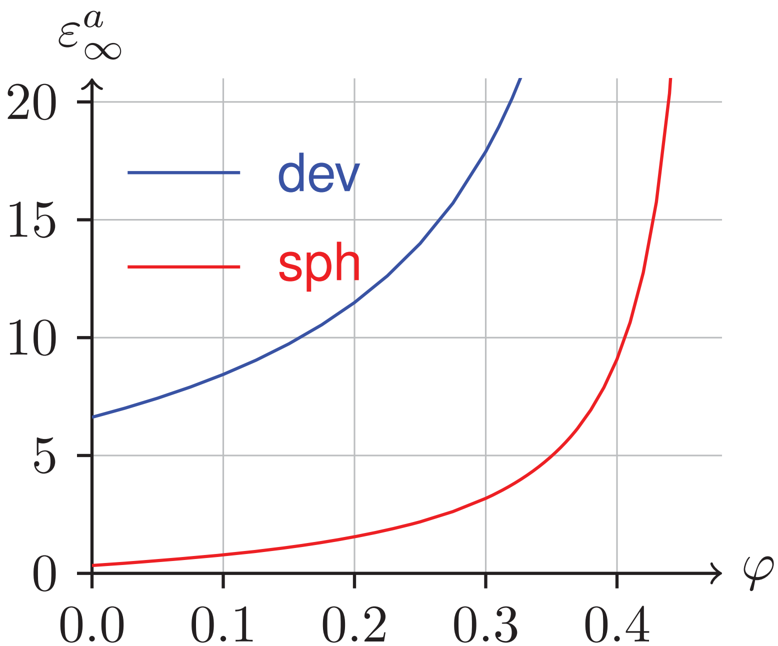


$r_{hd} = 0.12 \Rightarrow$ threshold $\varphi^c = 0.67$

Long-term creep ($t \gg \tau$)

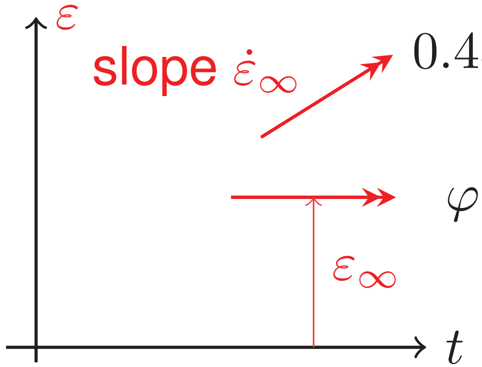


$\varphi < 0.48 \Rightarrow$ asymptotic strain



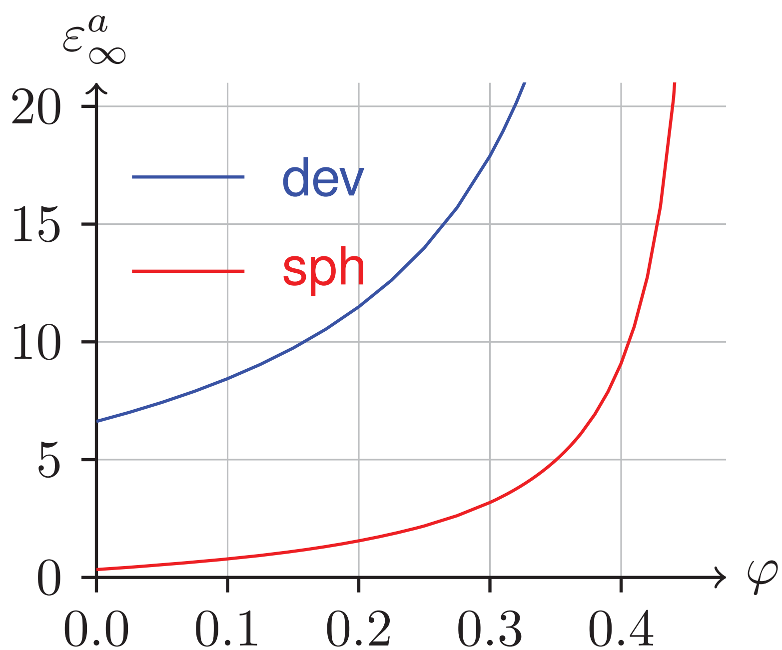
$r_{hd} = 0.12 \Rightarrow$ thresholds $\varphi^\infty = 0.48$

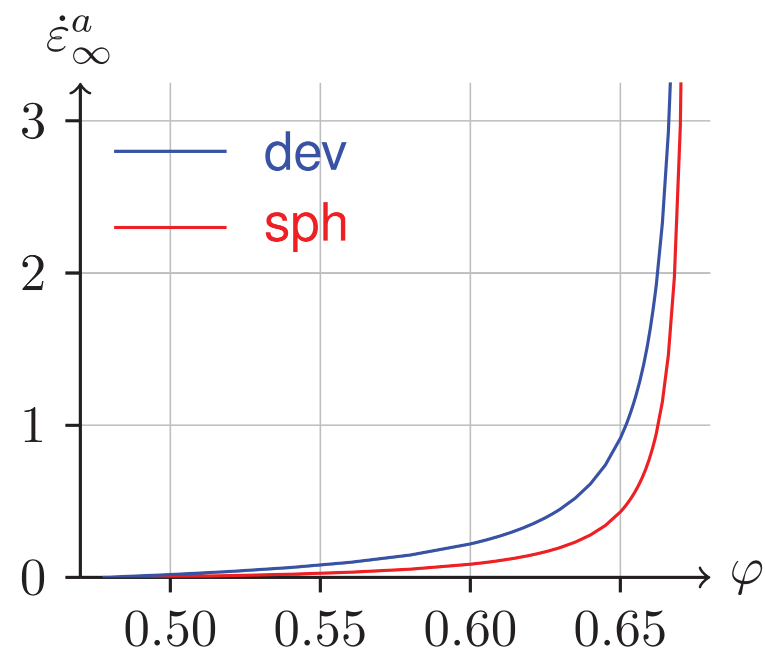
Long-term creep ($t \gg \tau$)



$0.48 < \varphi < 0.67 \Rightarrow$ asymptotic strain rate

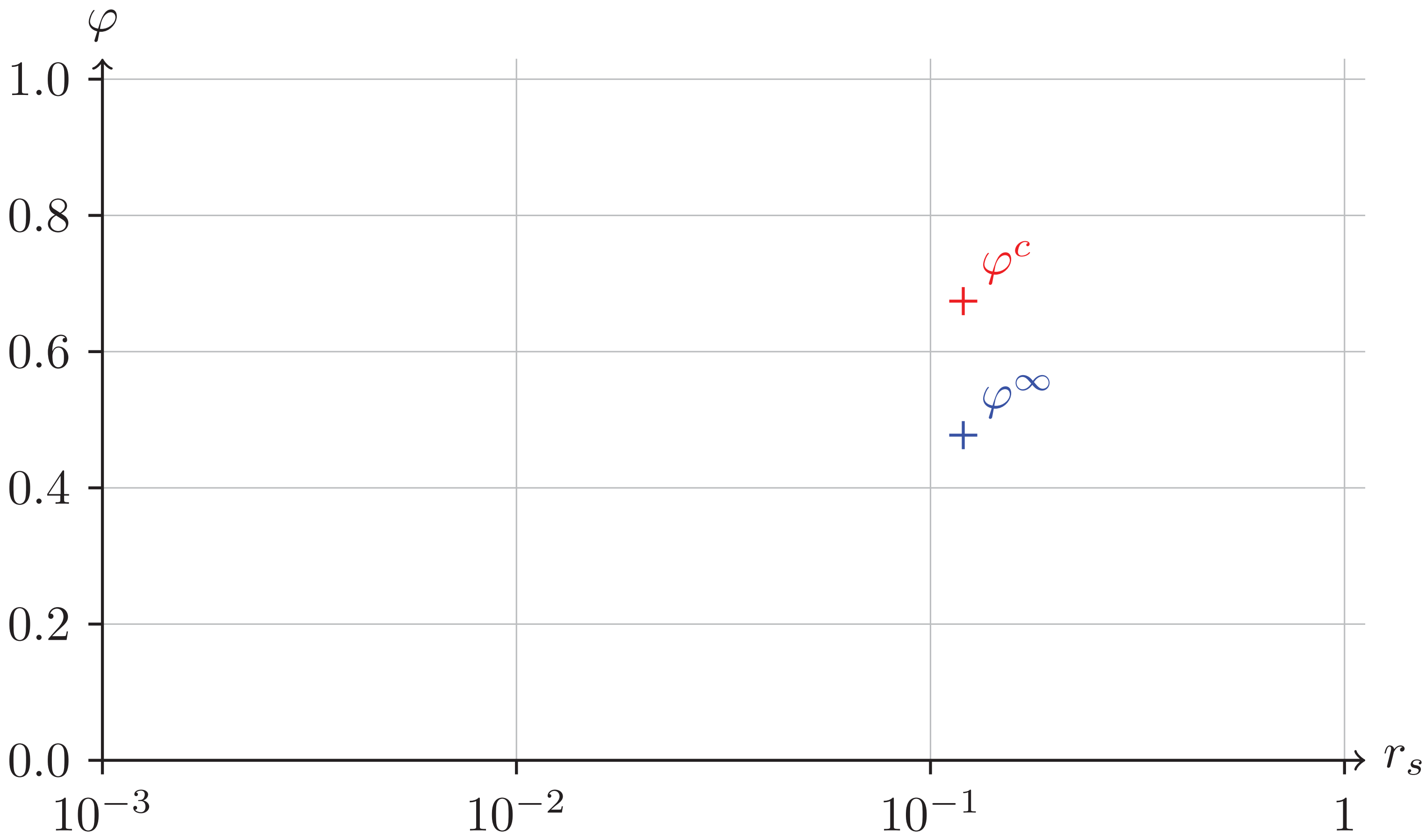
$\varphi < 0.48 \Rightarrow$ asymptotic strain





$r_{hd} = 0.12 \Rightarrow$ thresholds $\varphi^\infty = 0.48$ and $\varphi^c = 0.67$

Influence of the aspect ratio on the thresholds



[J. SANAHUJA, L. DORMIEUX. *Creep of a* C-S-H *gel: micromechanical approach.* IJMCE 37 (2010)]

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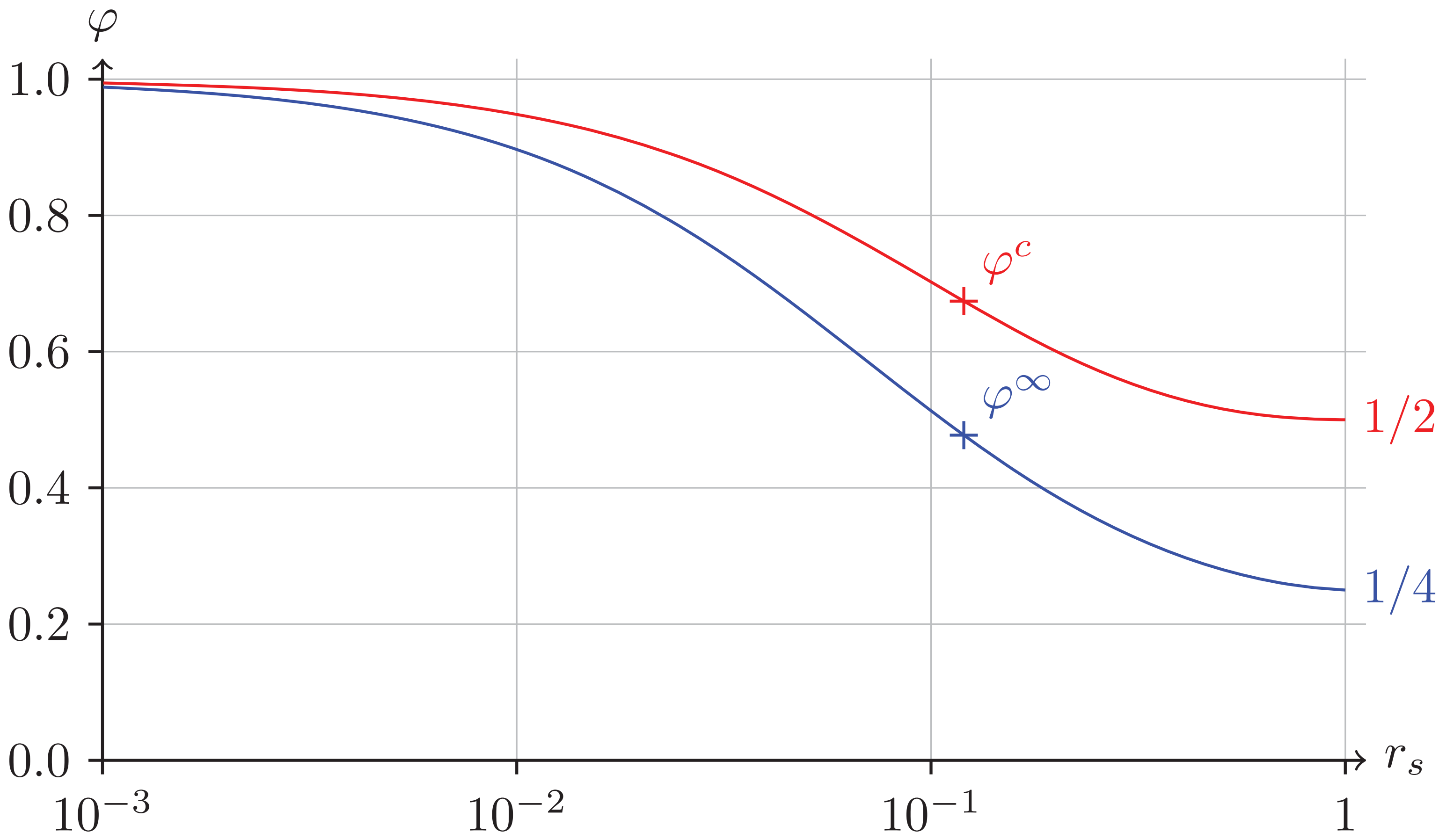

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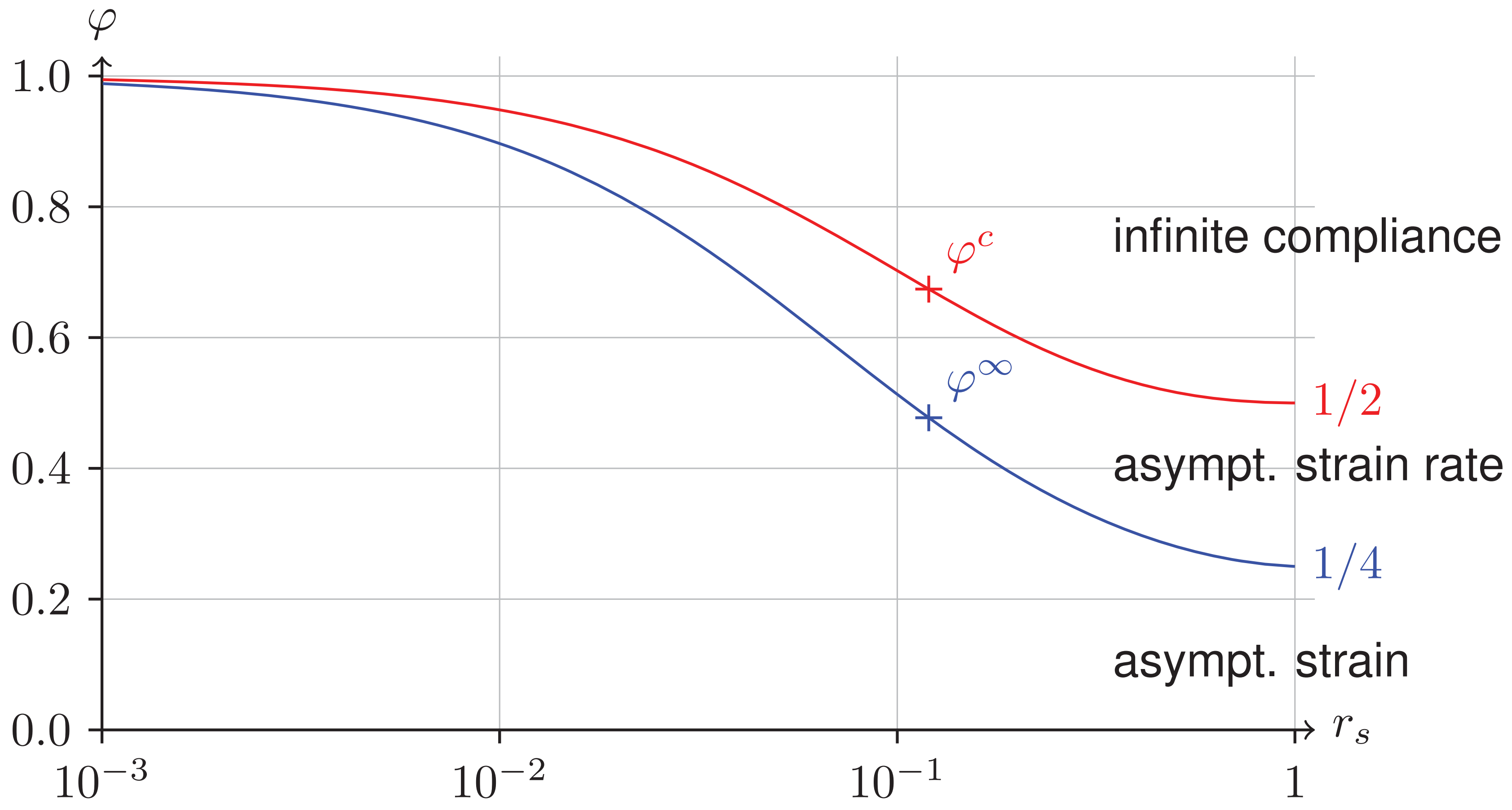

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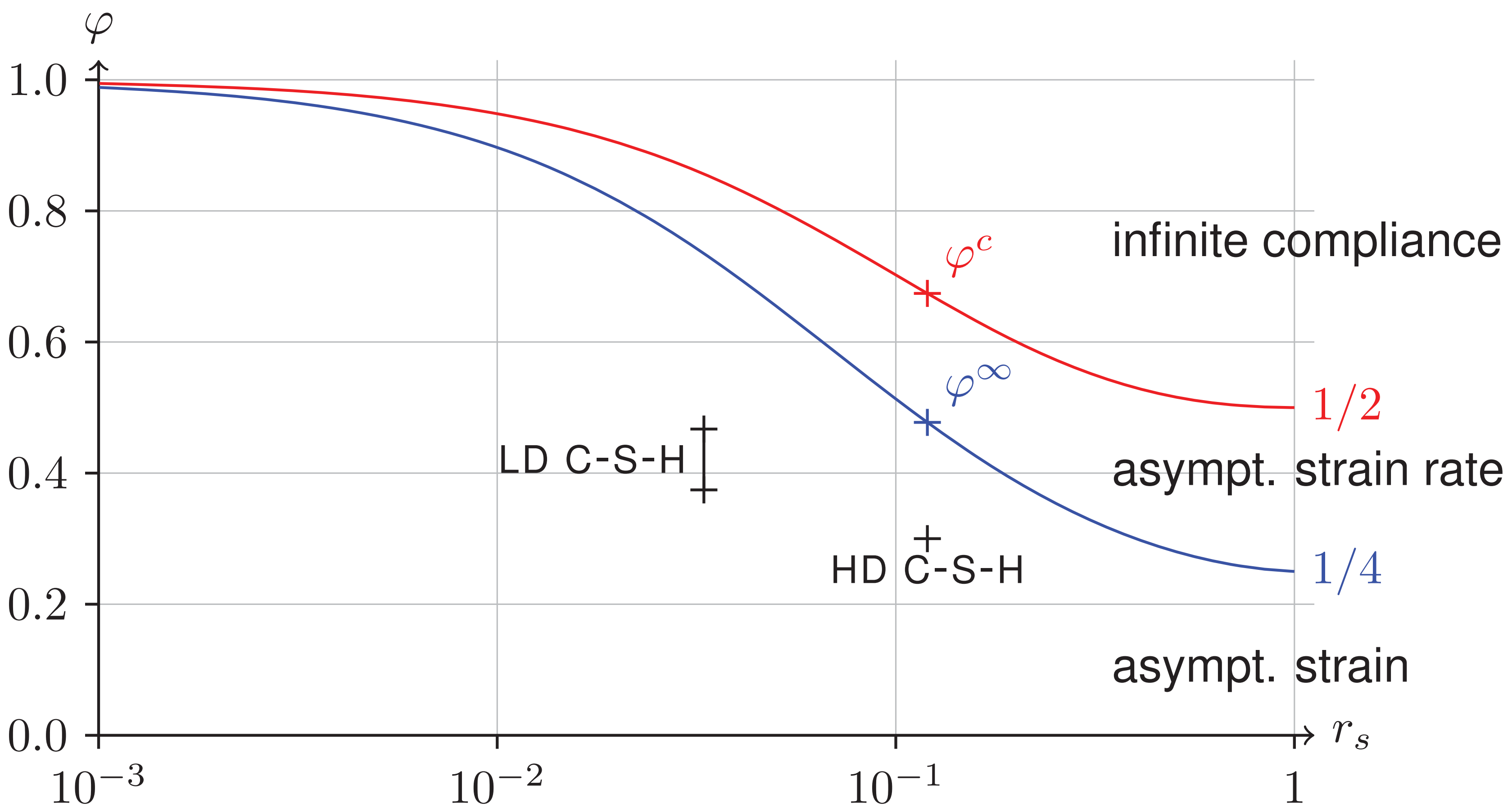

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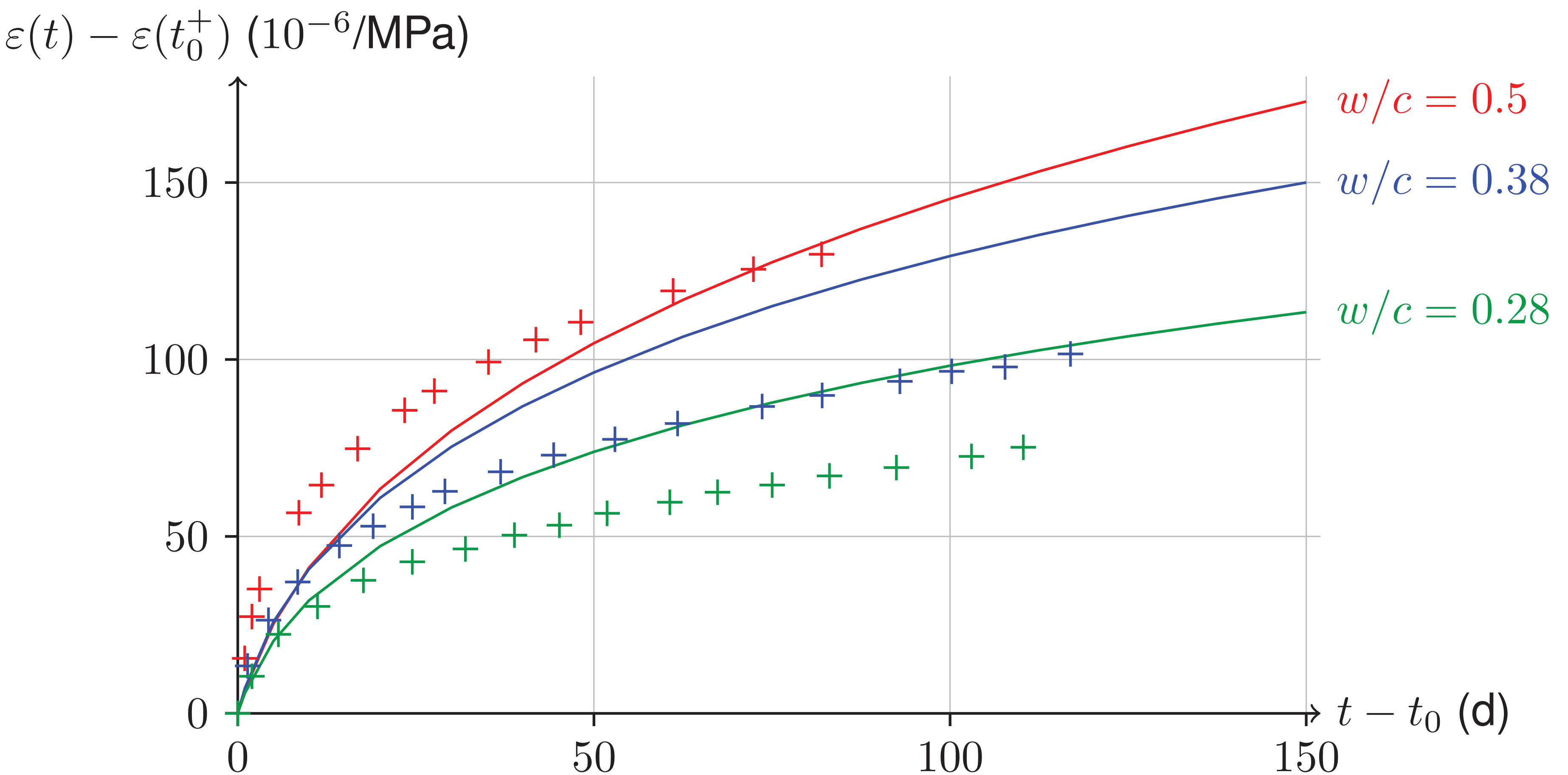
Creep of cement paste: VS experimental data

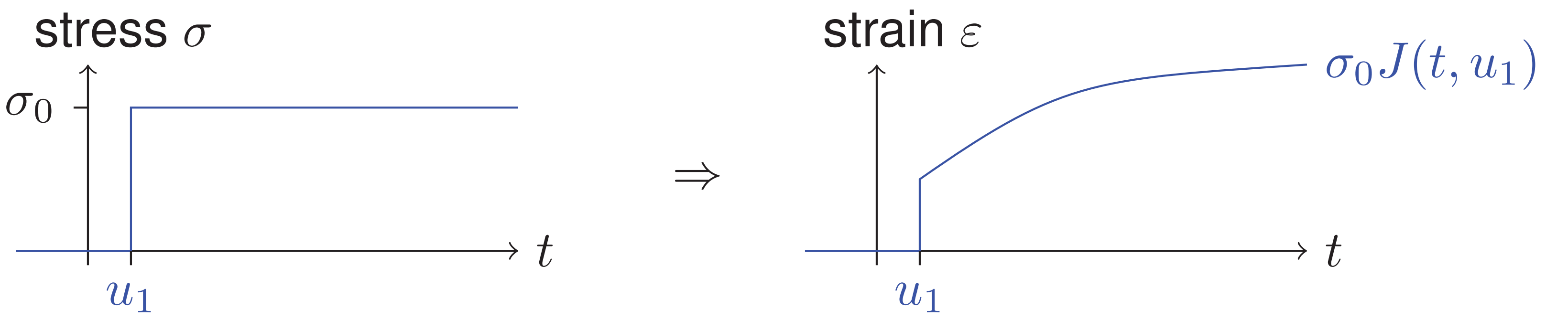
Experimental data: R. LE ROY Ph.D. thesis (1995), $t_0 = 28$ d
Model: $\alpha_0 \rightarrow \alpha^{ult}$ (parameters from elastic model + $\tau = 0.82$ d)



Outline

What's the matter with ageing?

Ageing viscoelasticity: compliance function $J(t,u) \neq J(t-u)$



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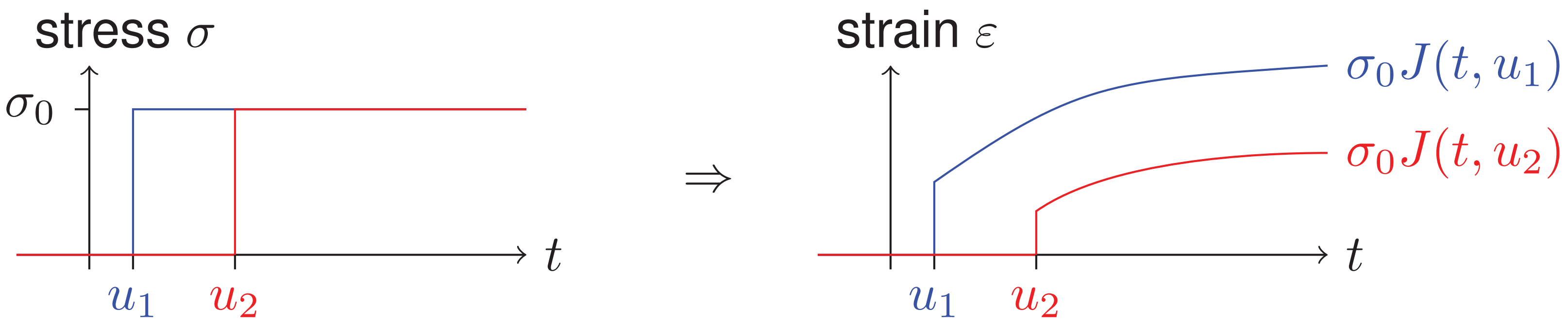

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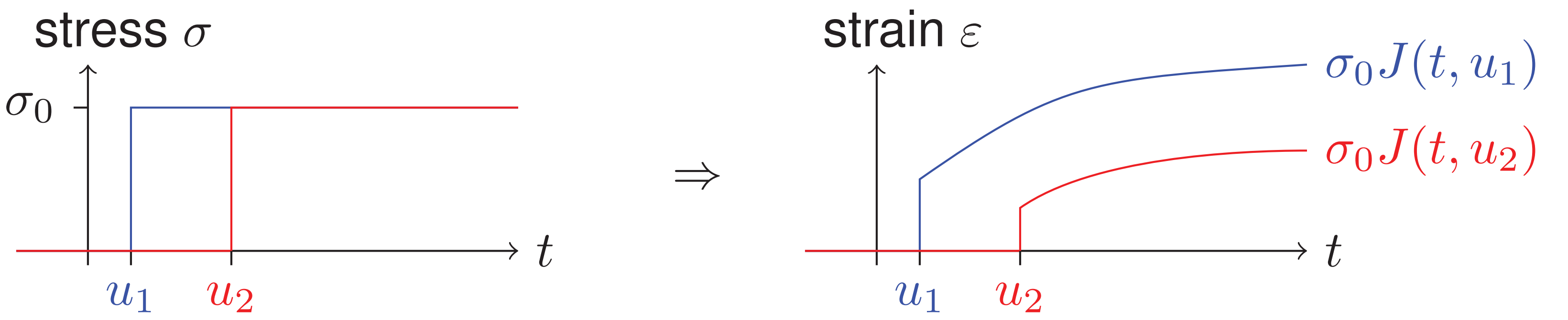
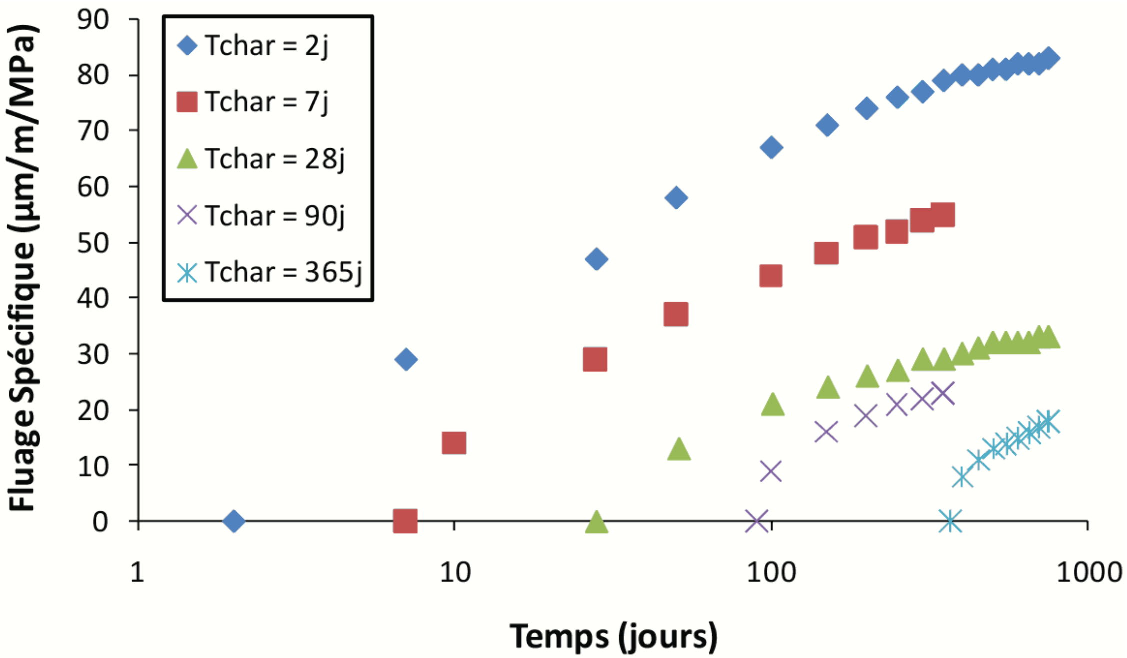


Concrete: basic creep tests, [Hanson, 1953] cited by [Briffaut, 2010]



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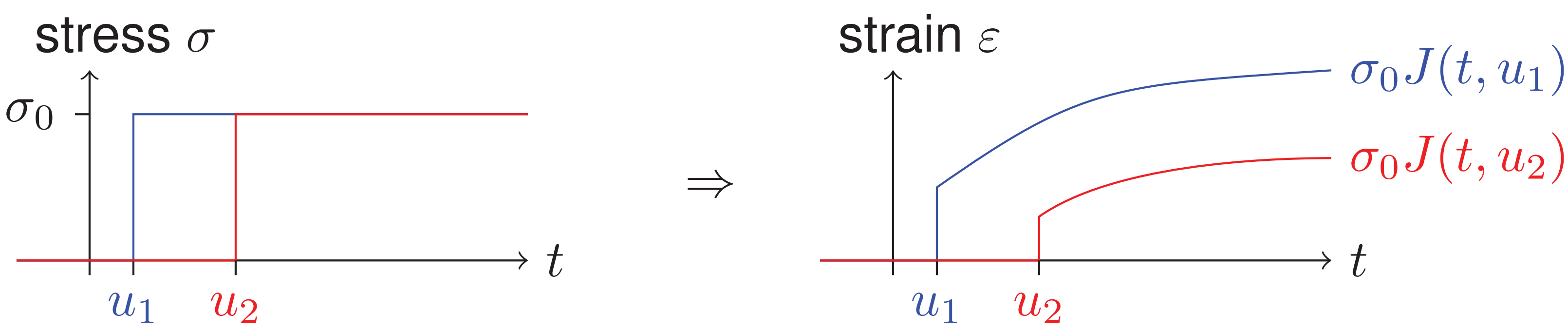

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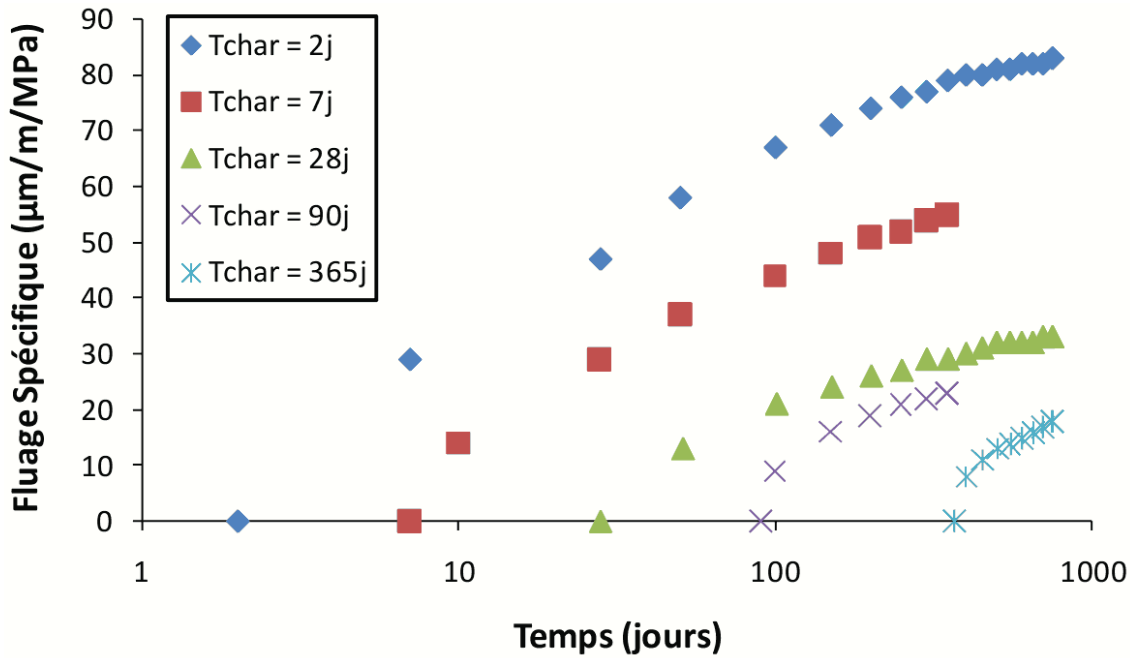

- test
  loading at $\approx$ 28 days
- structure
  loading at $>$ 1 year

How to compare both responses?

Ageing viscoel. homogenization, now made easy

Ageing local behaviours ⇒ Laplace-Carson transform inapplicable

- multilayered media [Maghous, Creus, 2003]
- random media:
  a few recent incremental approaches [Masson et al., 2009, 2012]
  solidifying non ageing materials [Scheiner, Hellmich, 2009]

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in ageing linear viscoelasticity

Inputs/outputs: full relaxation $R(t, u)$ functions, time-sampled

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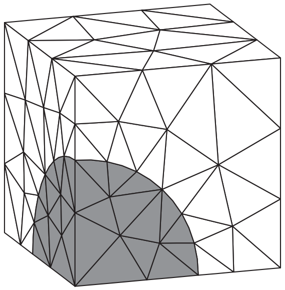
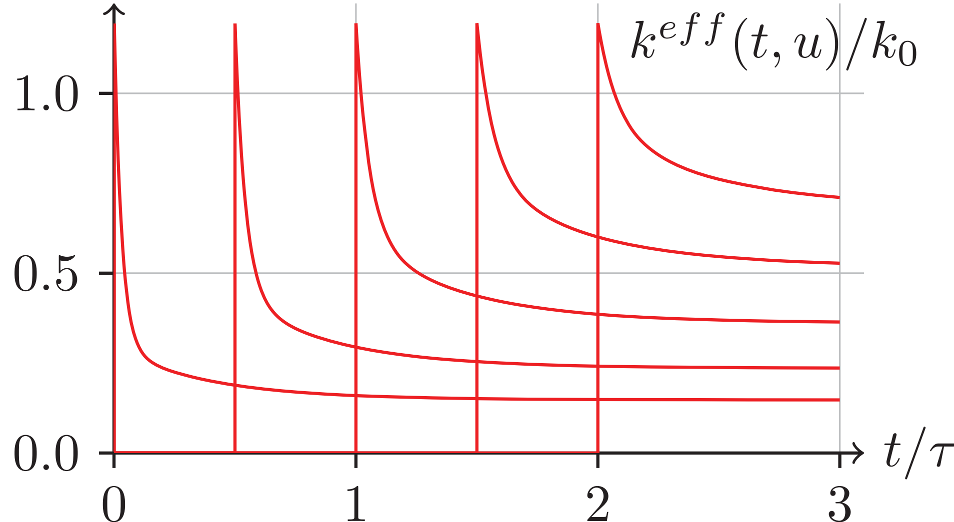


FEM (13 min)



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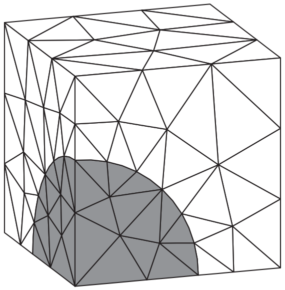
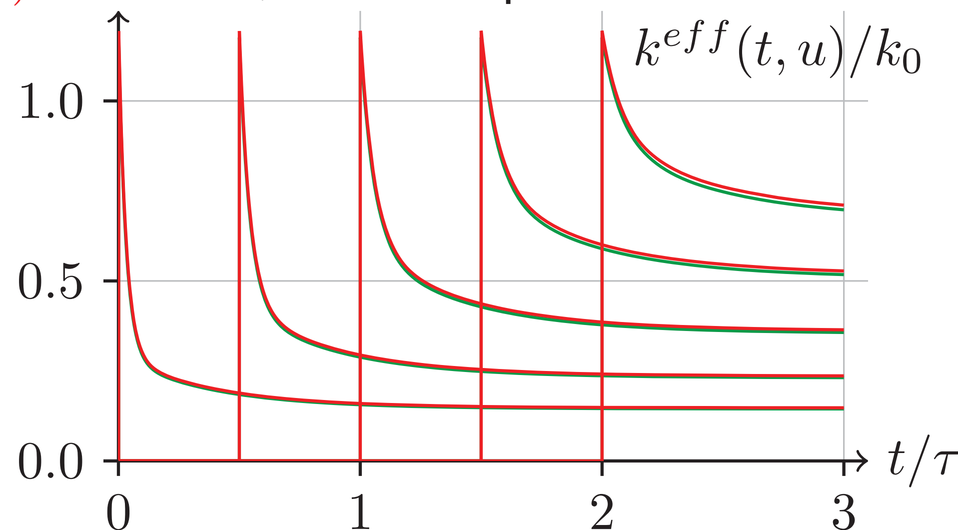


FEM (13 min)

VS schemes

dilute (<0.5 s)



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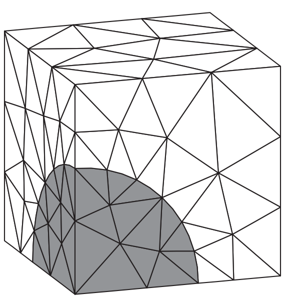
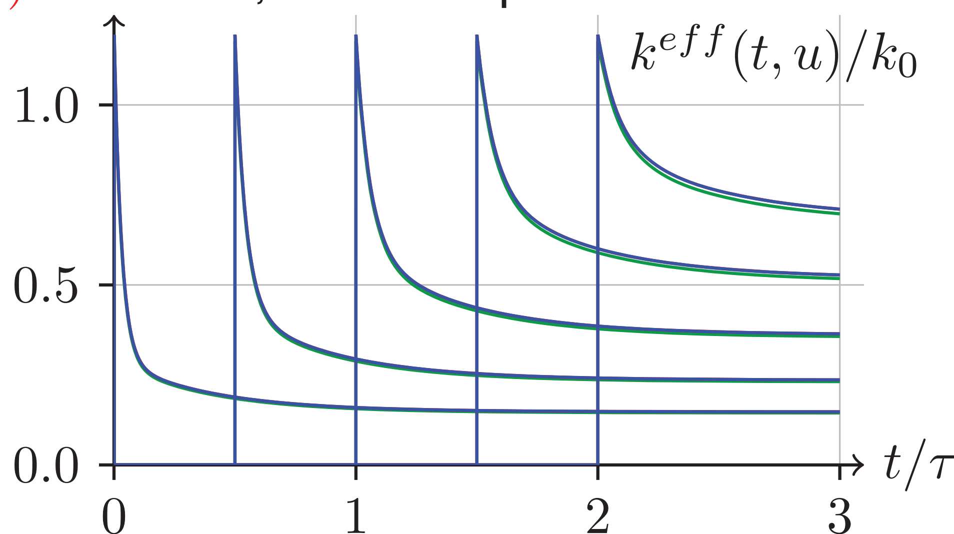


FEM (13 min)

VS schemes

dilute (<0.5 s)

MT (0.6 s)



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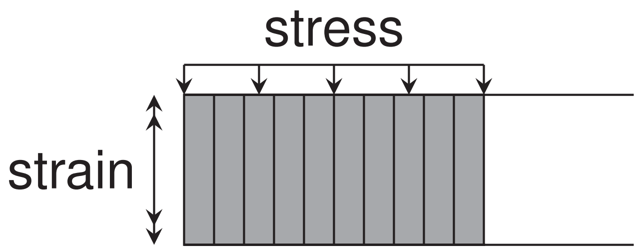
Solidification theory from Bažant

Solidification theory: non ageing material
+ progressive precipitation ⇒ effective ageing behaviour



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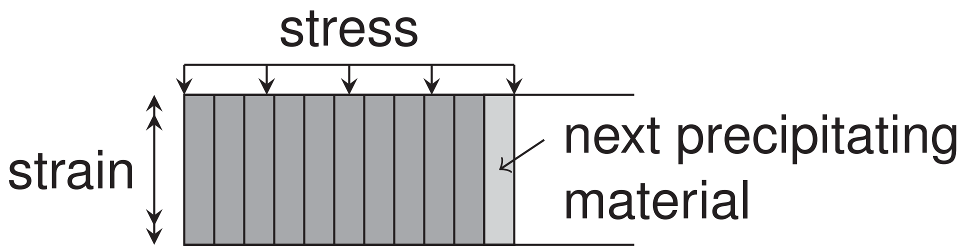

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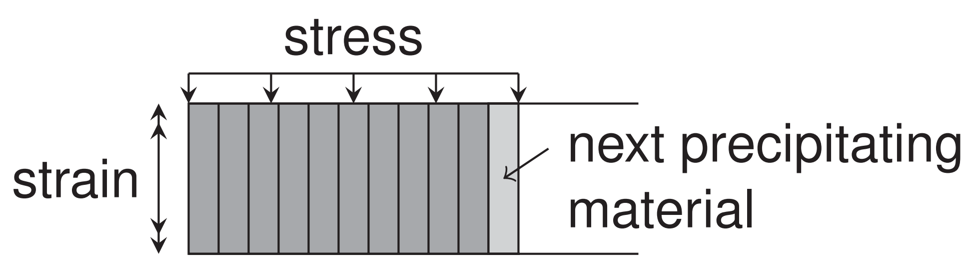
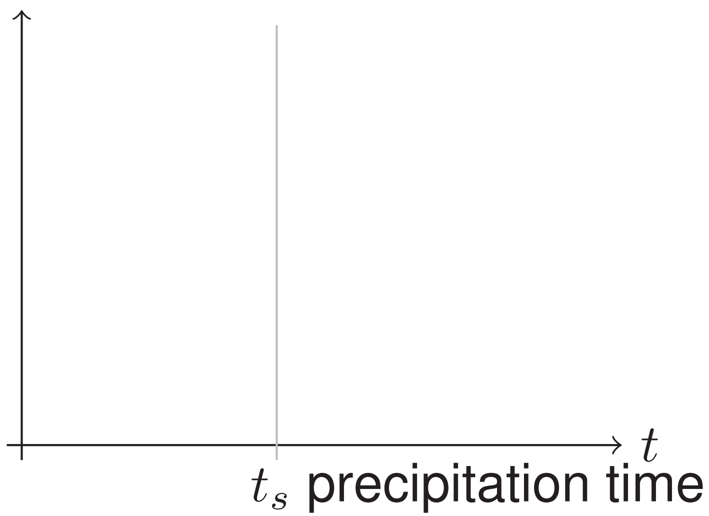


Elementary precipitating material



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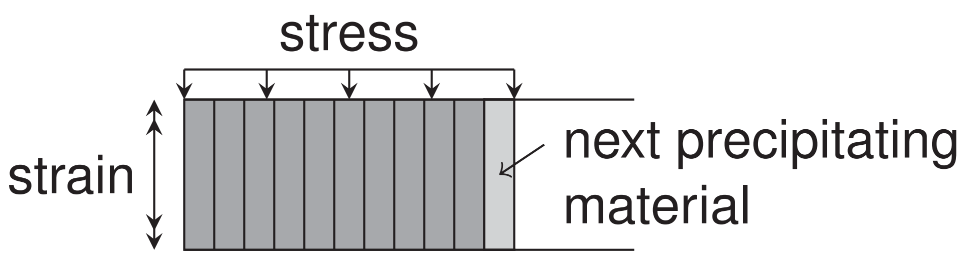

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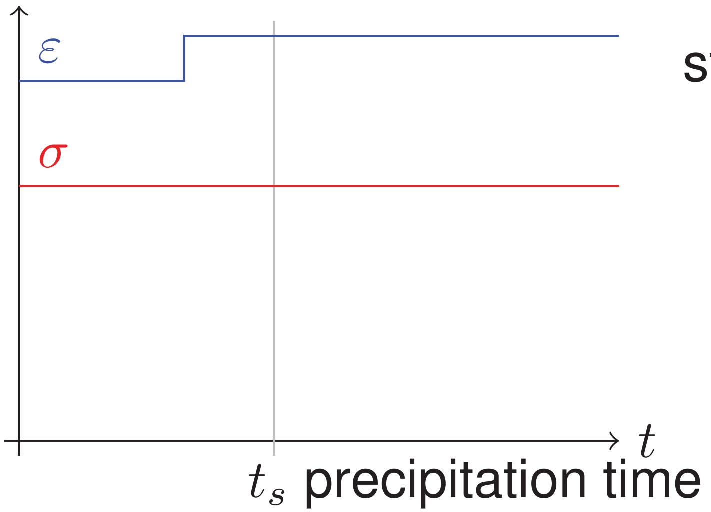

strain loading before precipitation

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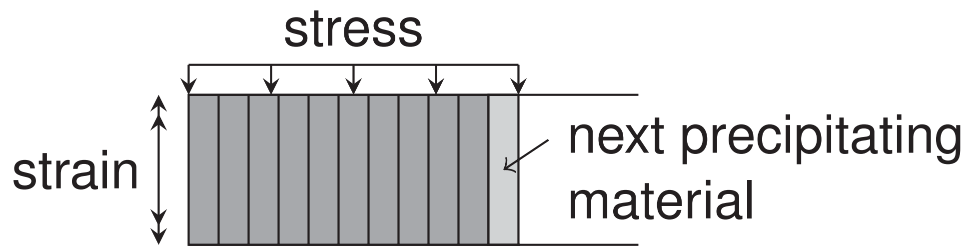

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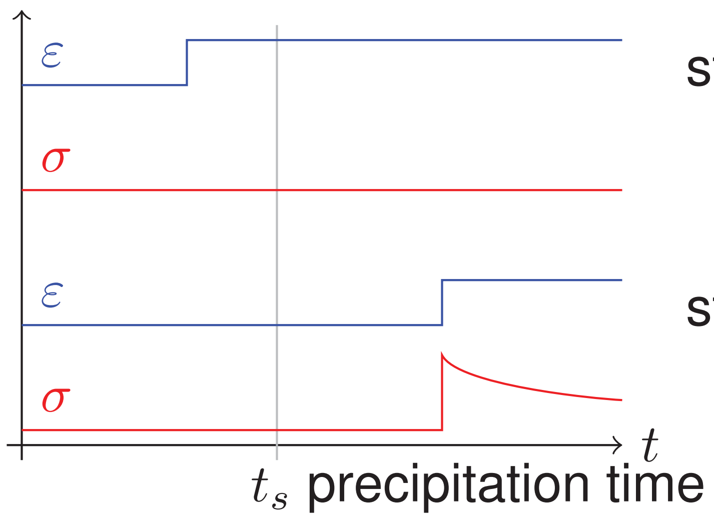

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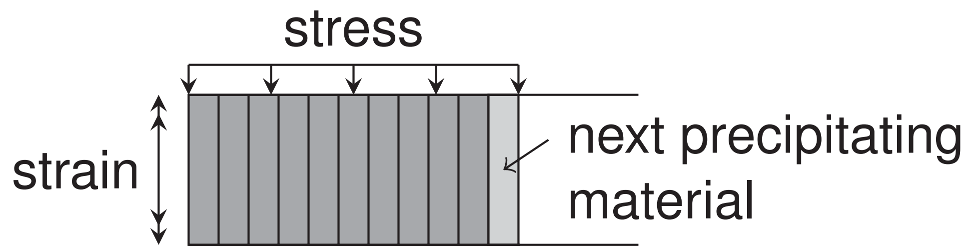

Elementary precipitating material
can be replaced by a (fictitious) ageing linear viscoelastic material

Solidification theory from Bažant

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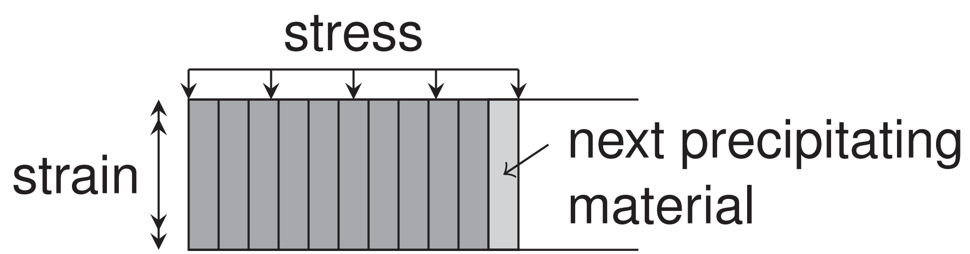

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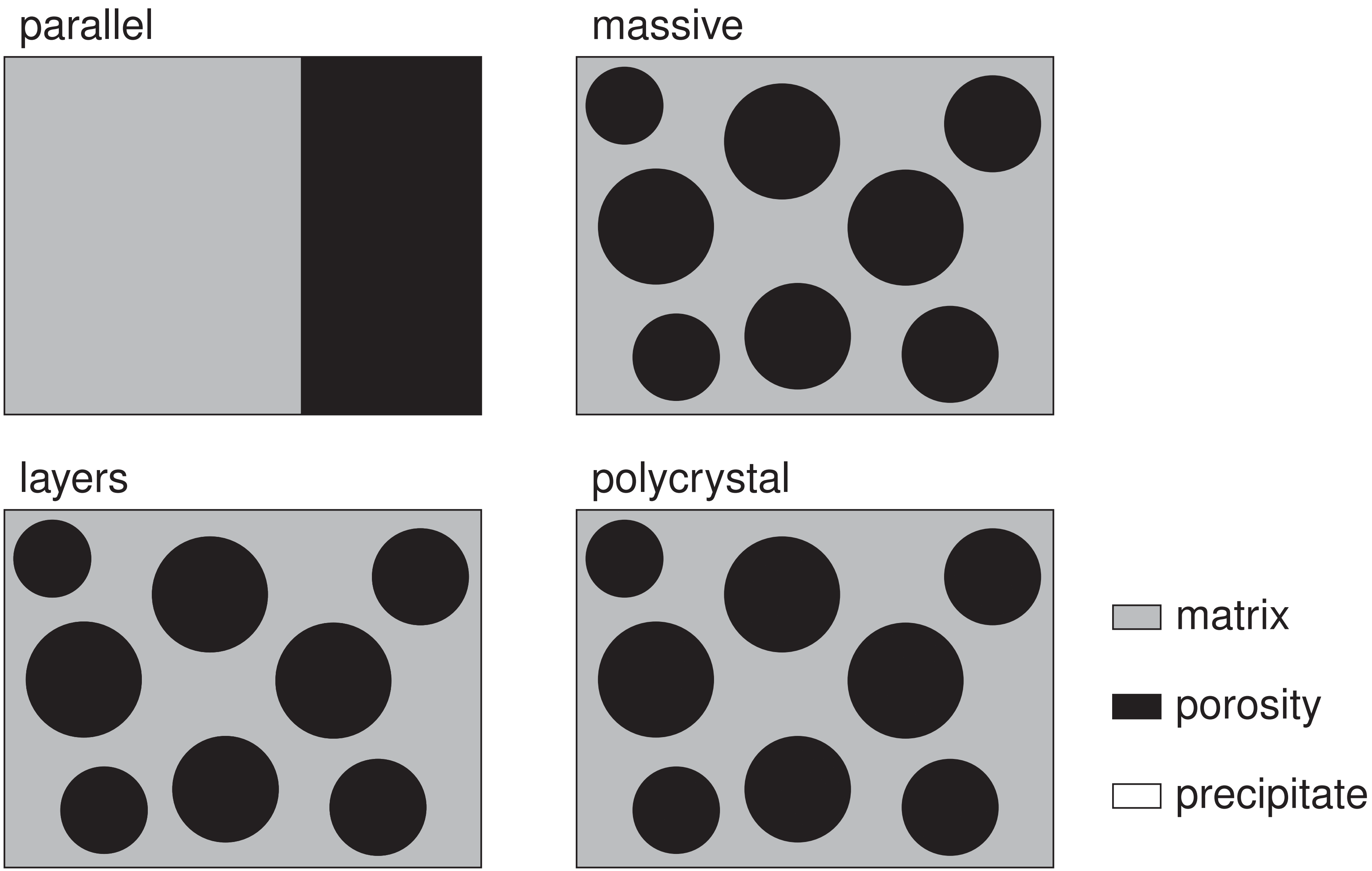
Micromechanical extension: main ideas

- progressive precipitation ⇒ N ageing viscoelastic phases
- evolving microstructure ⇒ constant microstr. + ageing phases
- precipitation mechanism → morphology of the N phases
- precipitation kinetics → precipitation time t_s of each phase
- take advantage of ageing viscoelastic homogenization

Application: investigation of precipitation mechanisms



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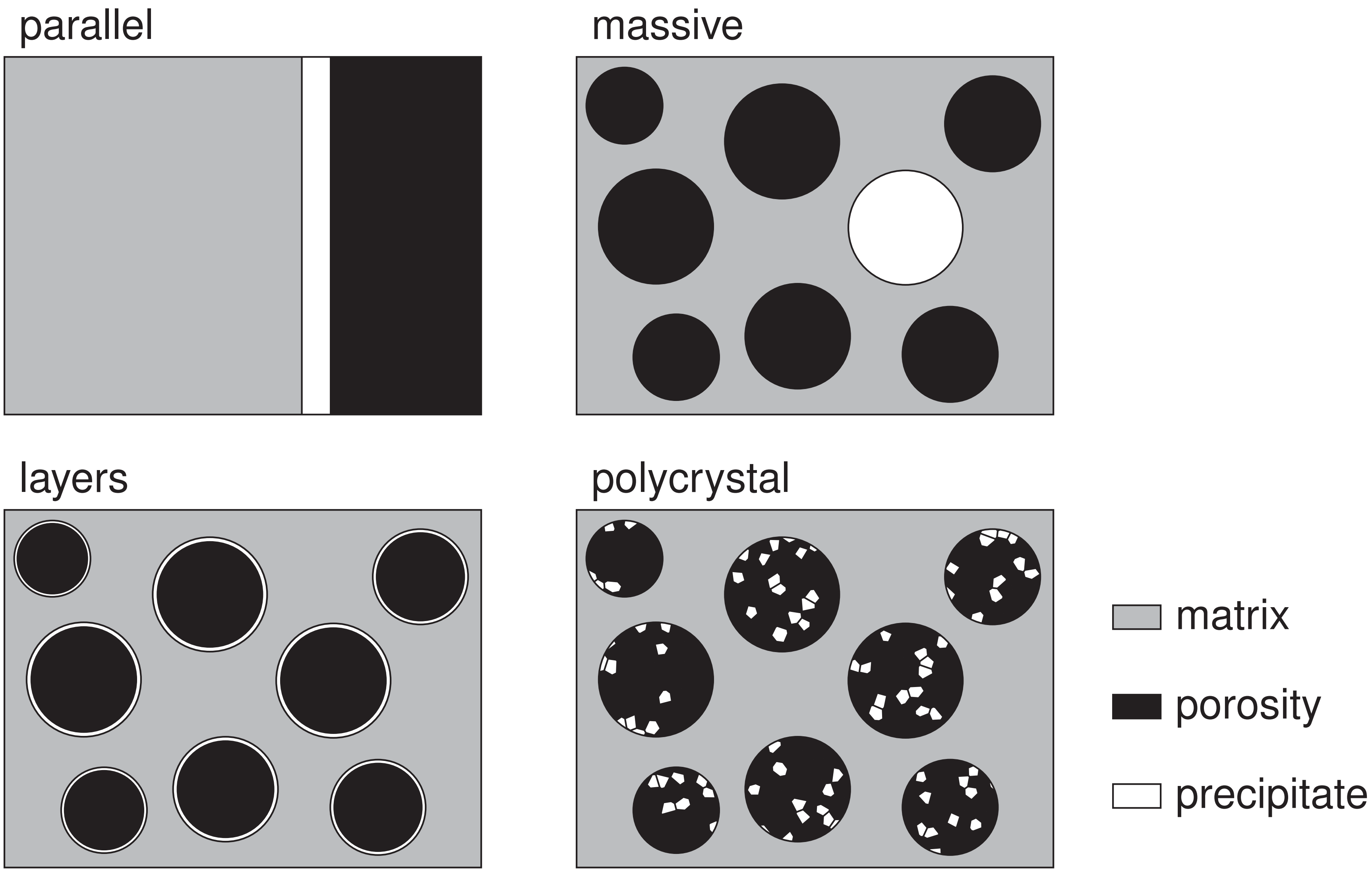

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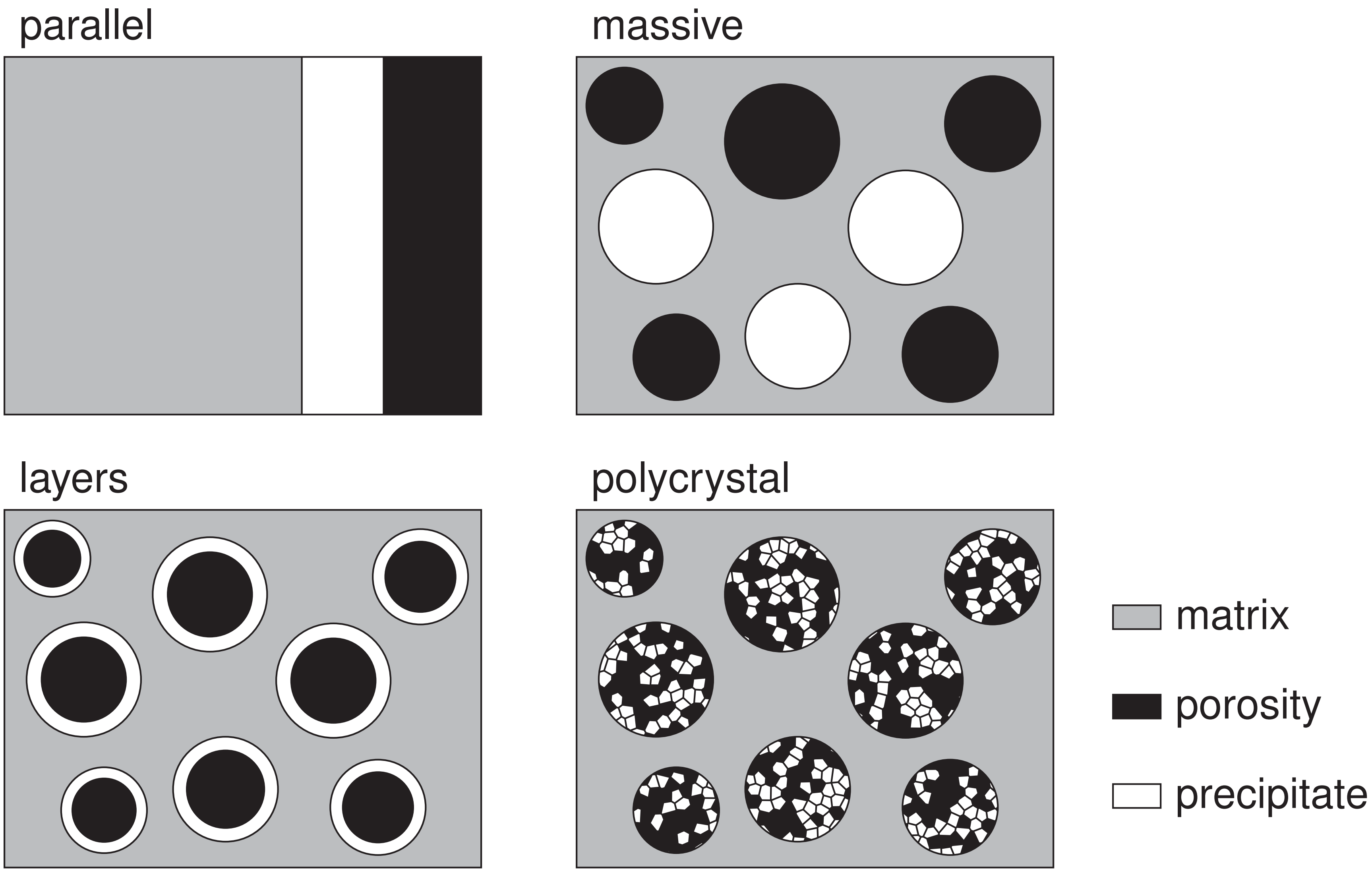

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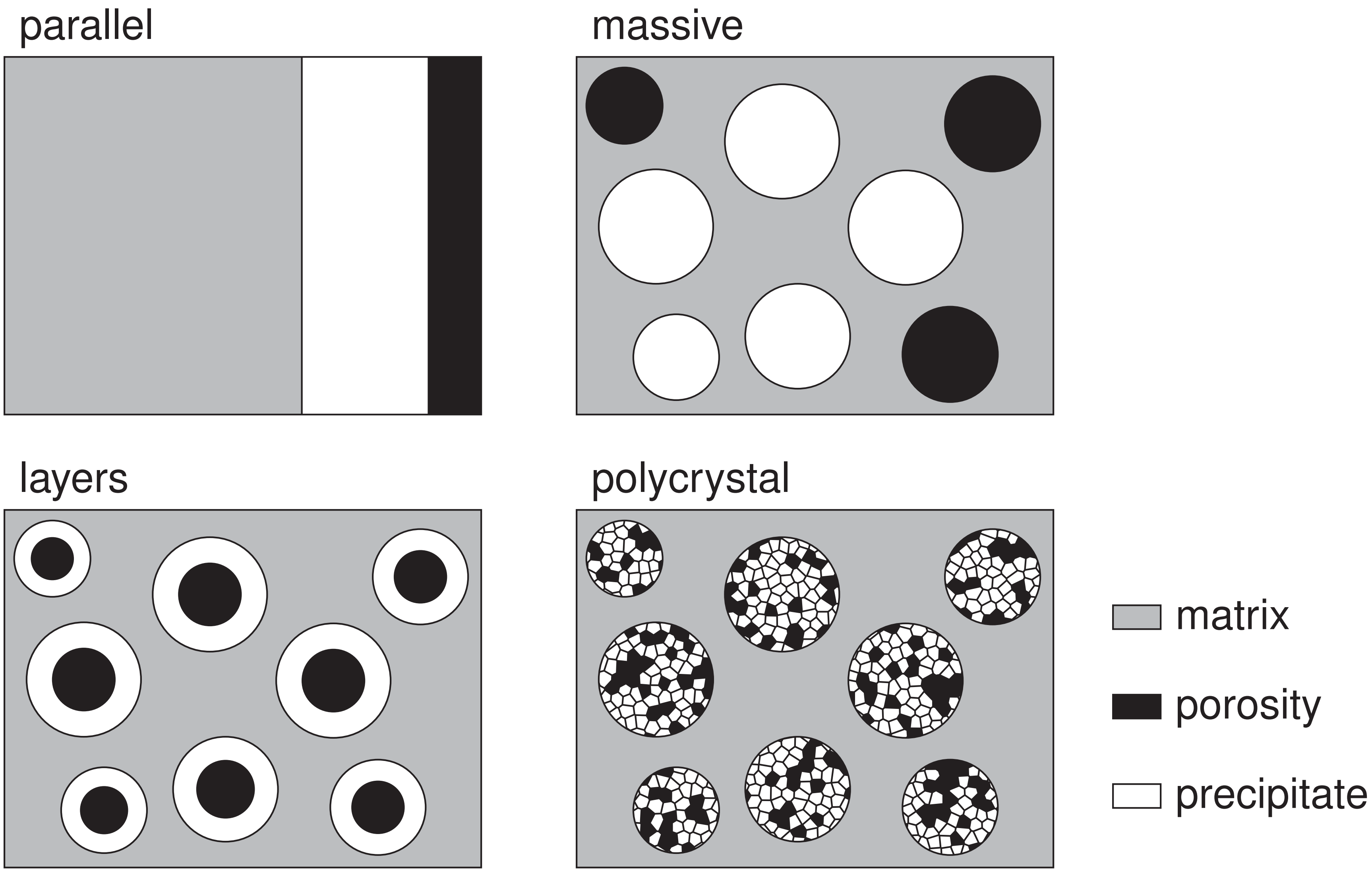
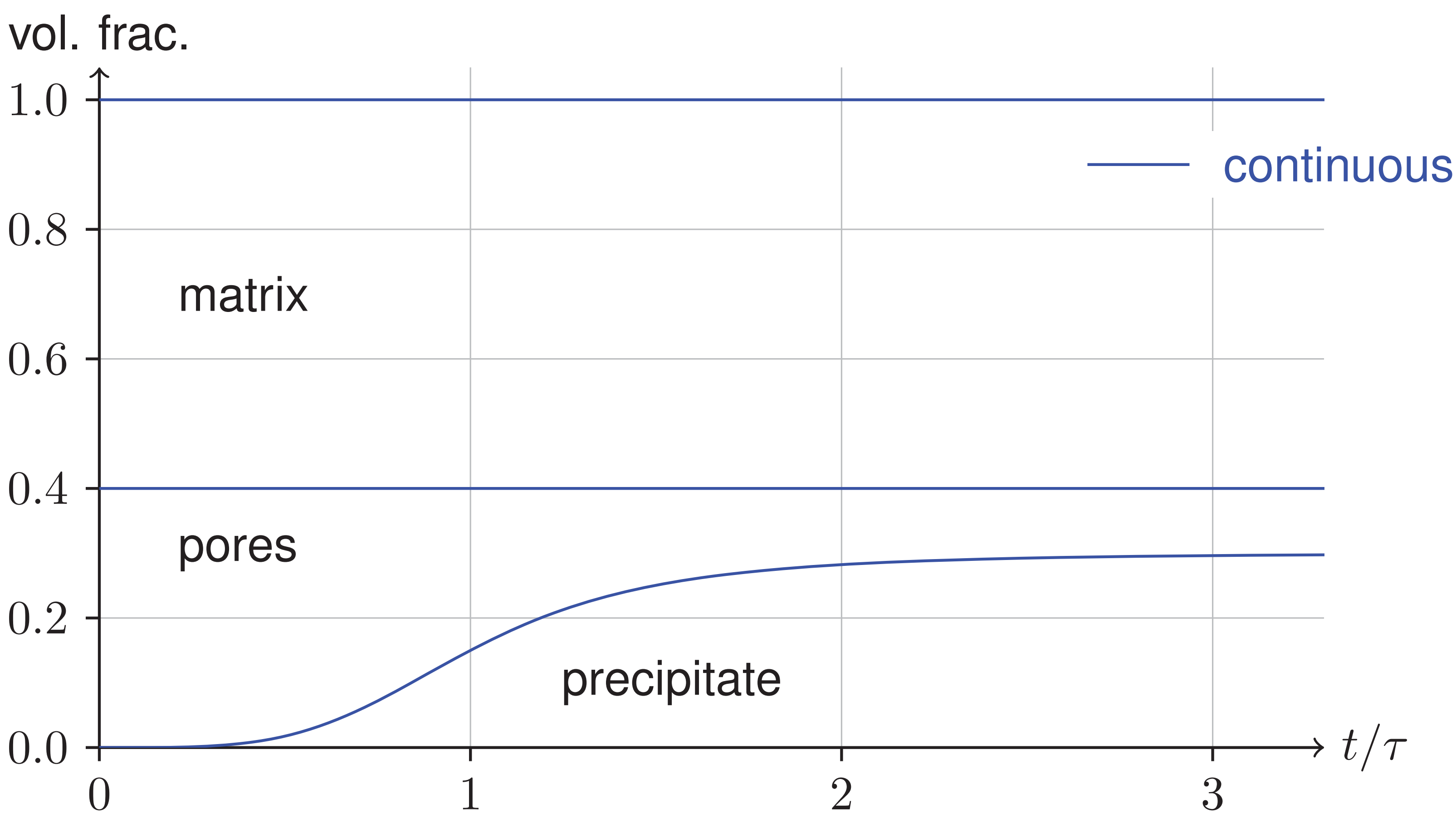


Precipitation kinetics

$$f_{prec}(t) = f_{prec}^{\infty} \frac{(t/\tau)^4}{1 + (t/\tau)^4}$$



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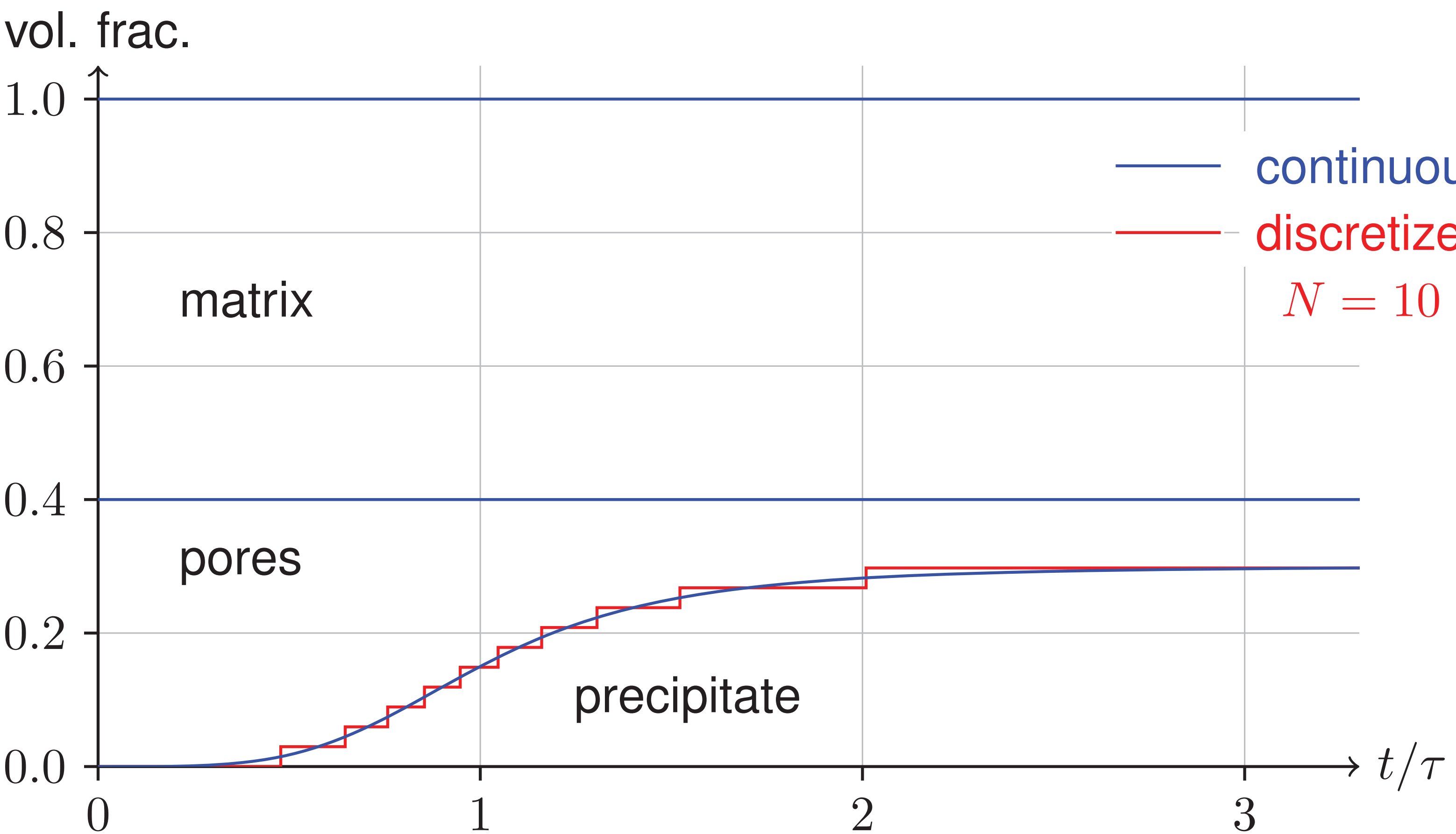
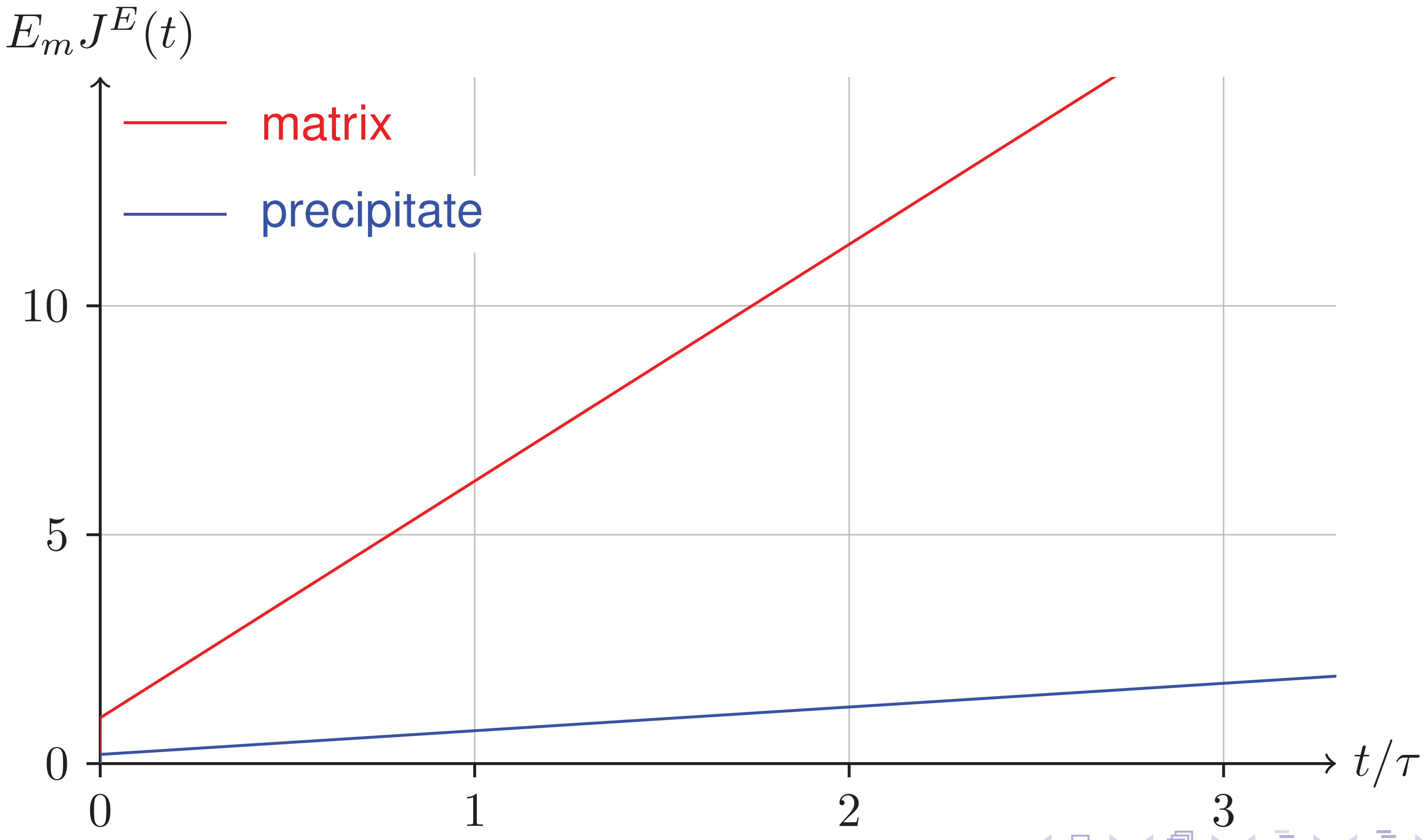
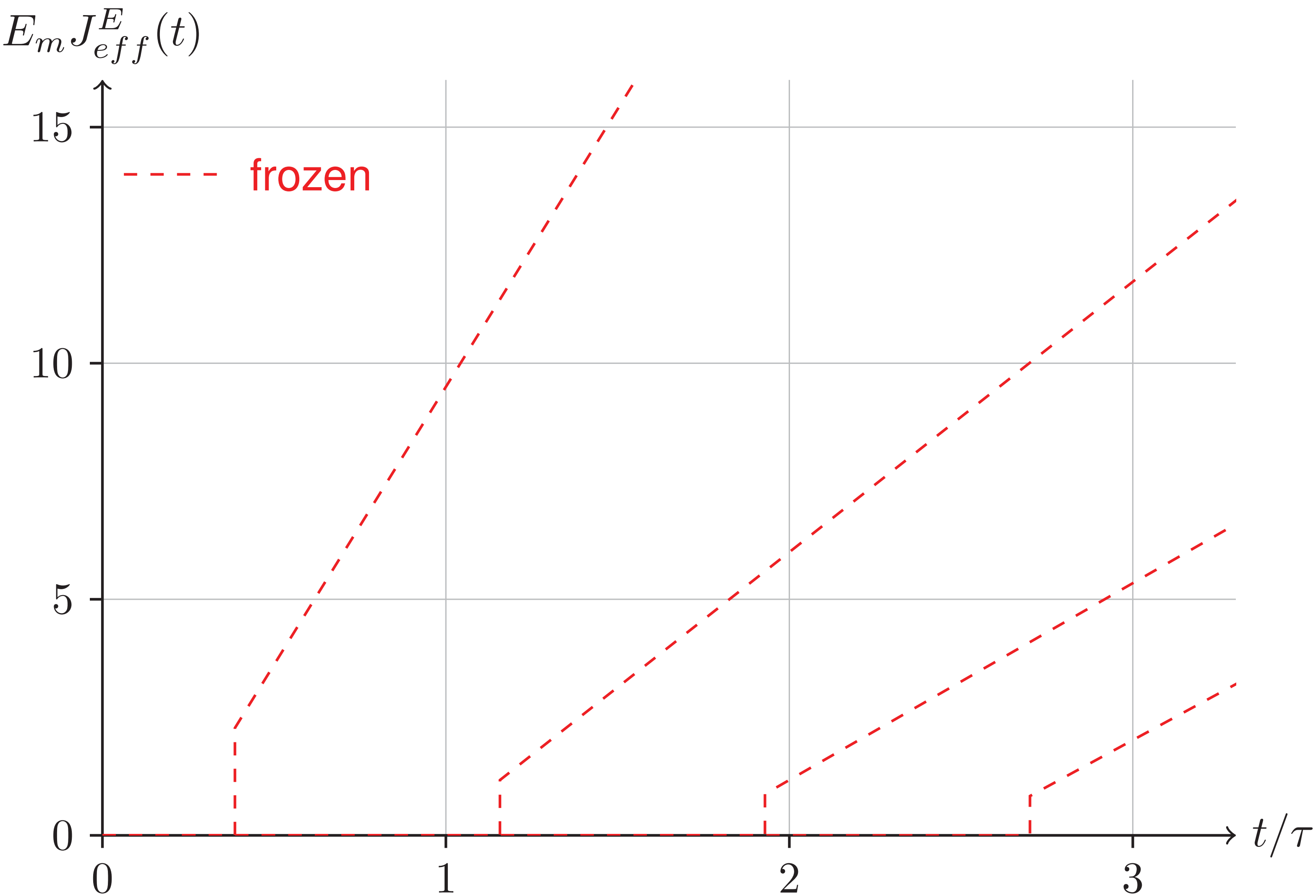


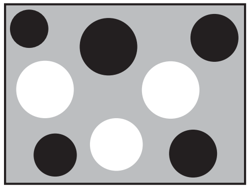
Matrix and precipitate behaviours

- isotropic non ageing linear viscoelastic
- constant Poisson ratio, Maxwell rheological model



Results wrt. more classical approaches





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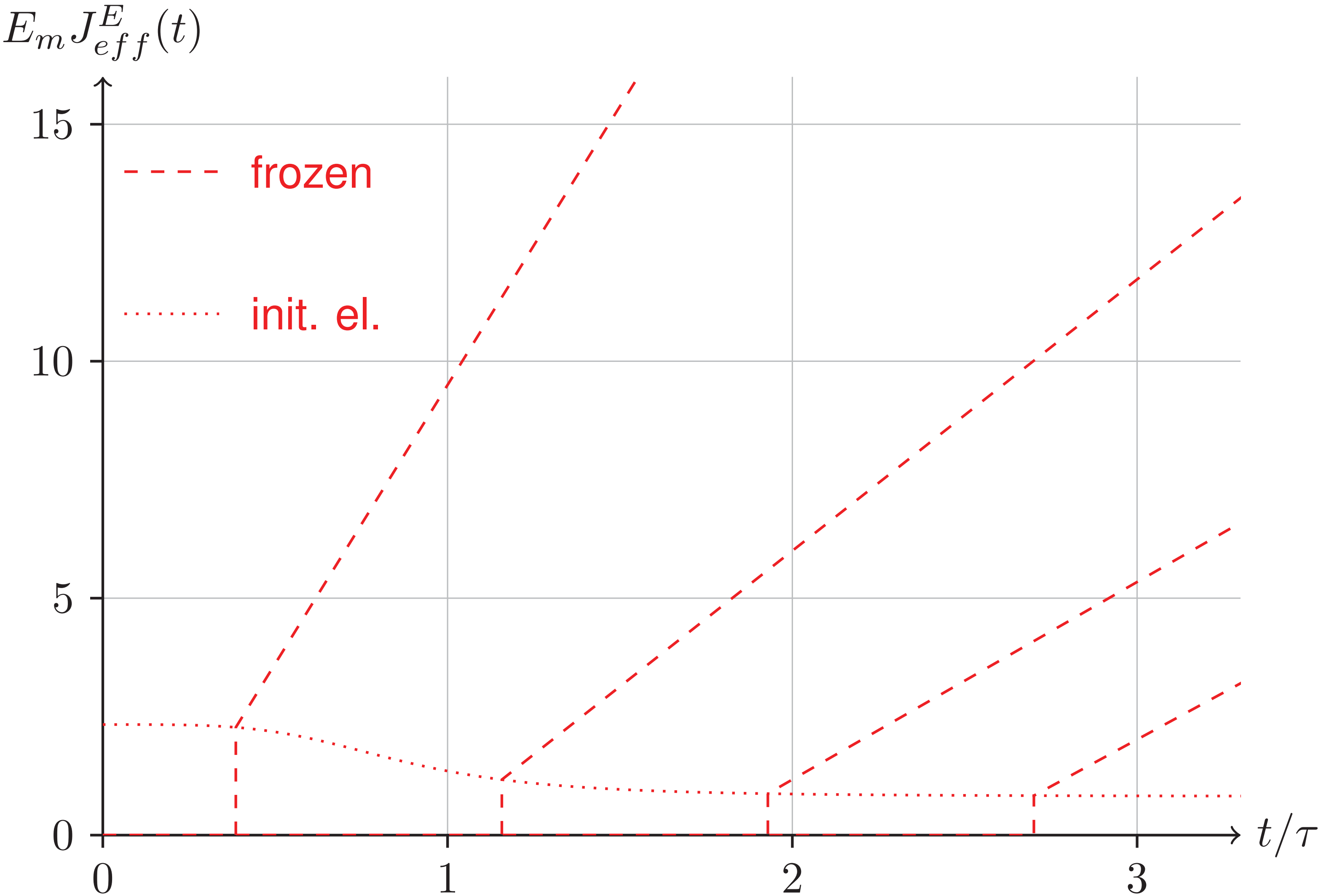

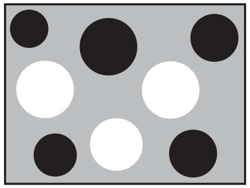

massive

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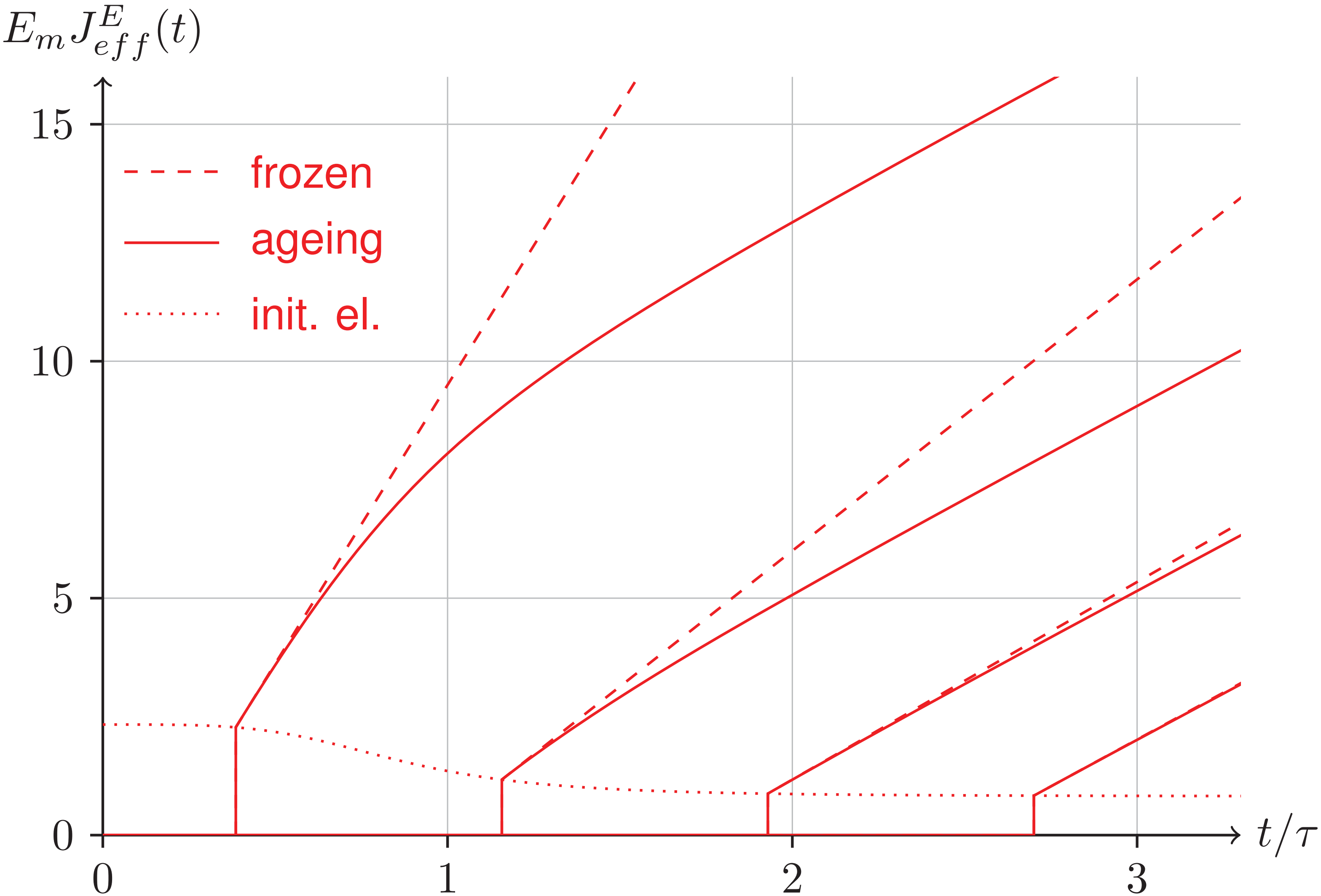
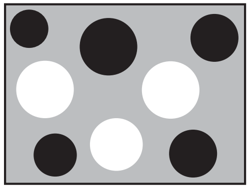
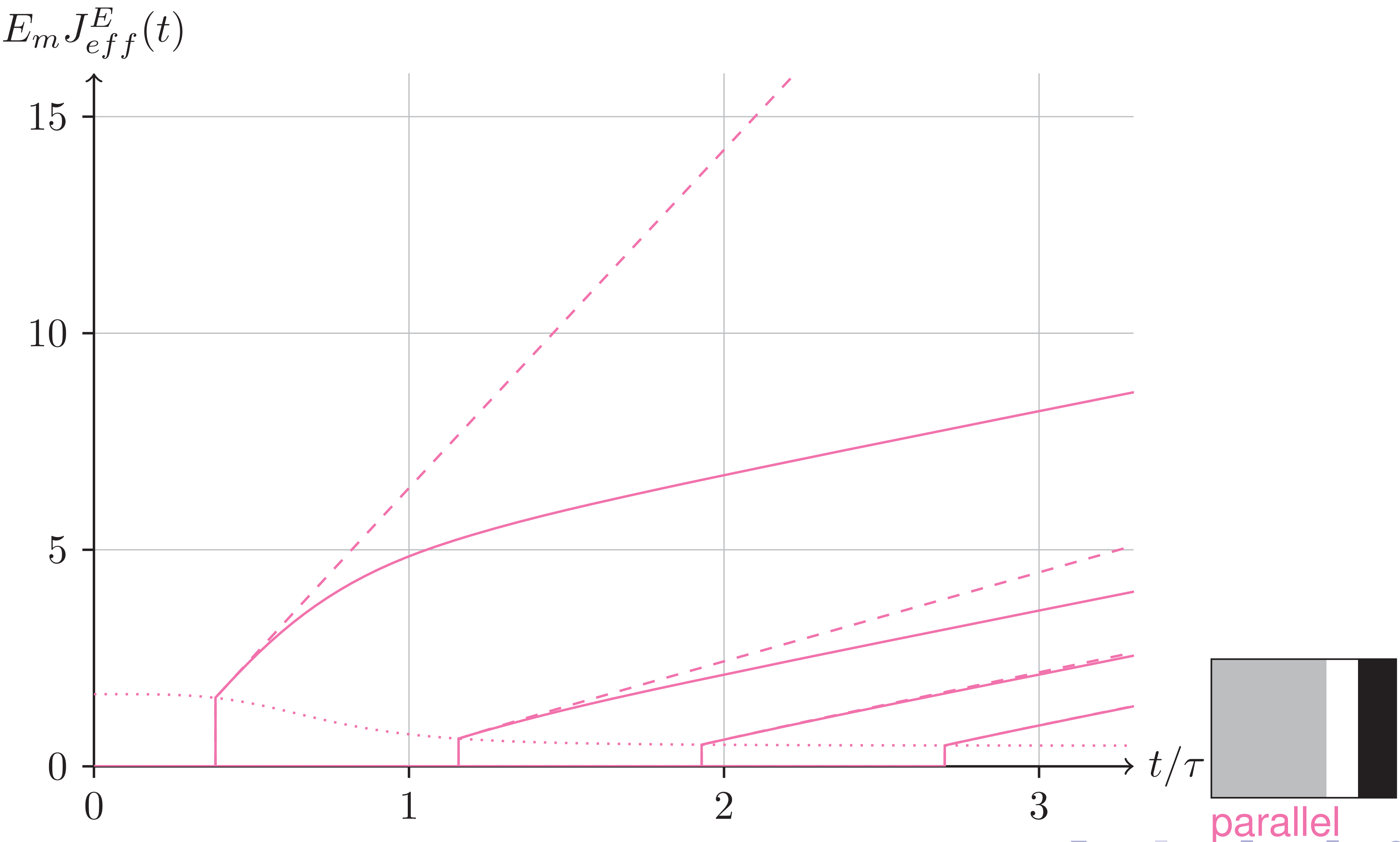




$N = 100$
ageing
phases

Results: effect of precipitation mechanism



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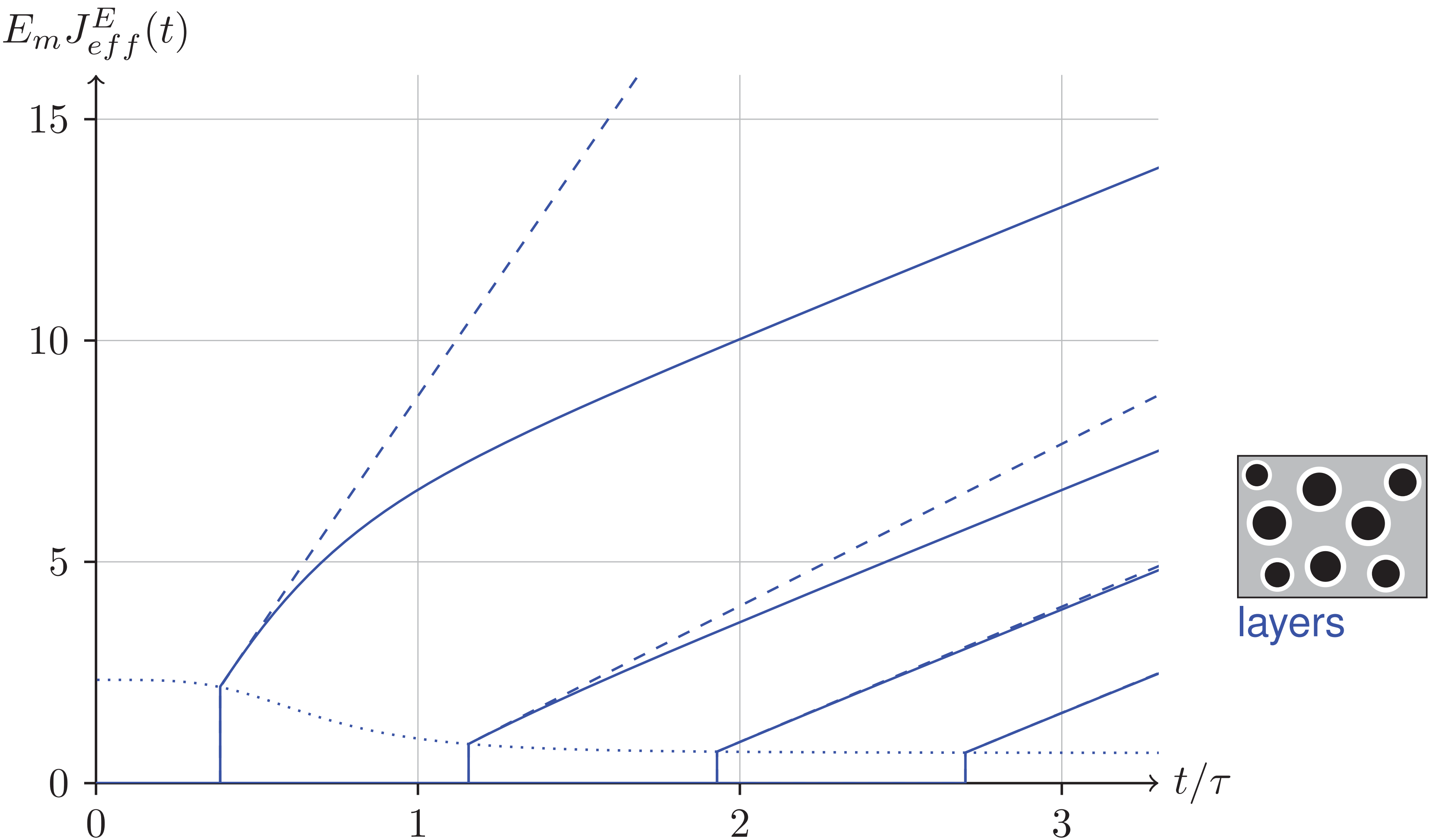

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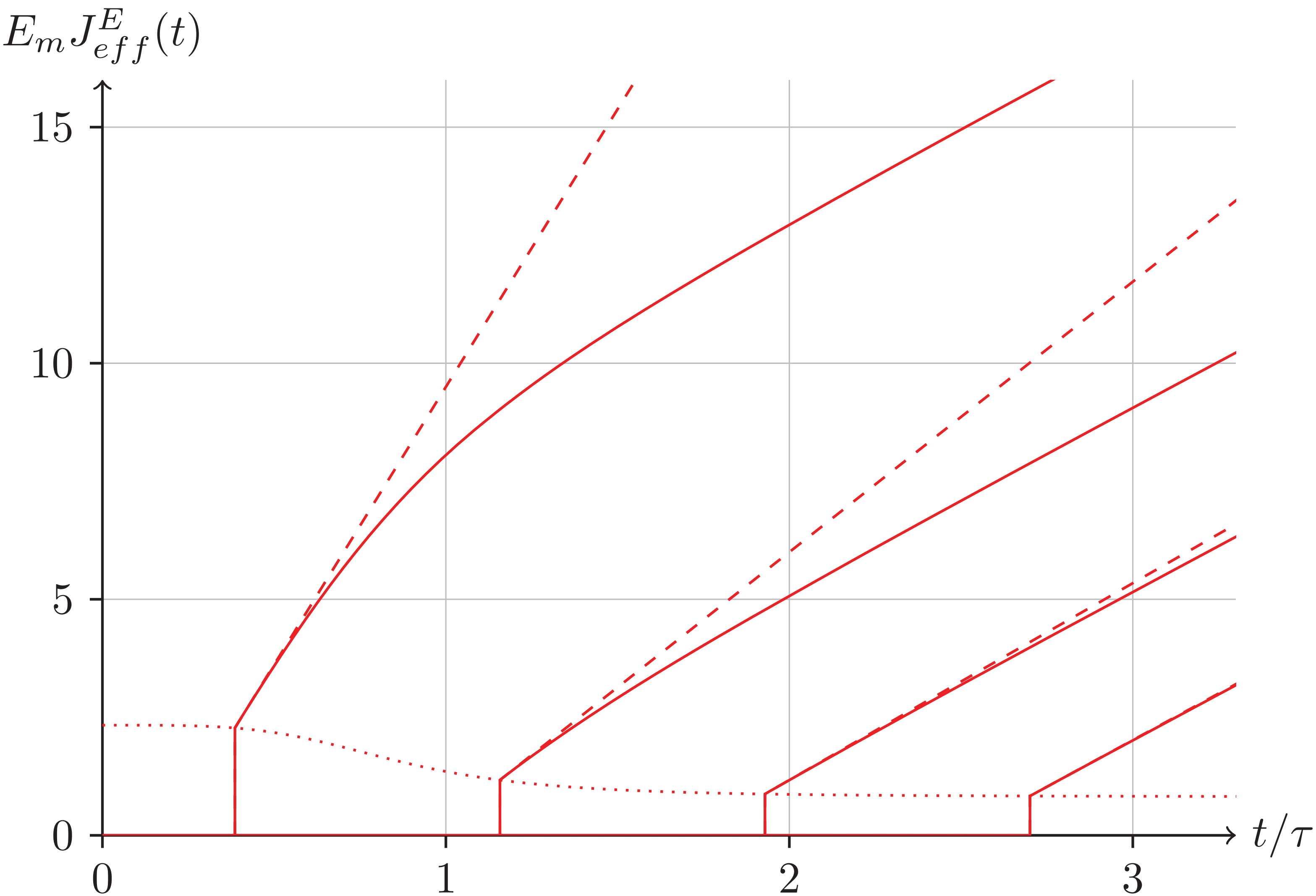
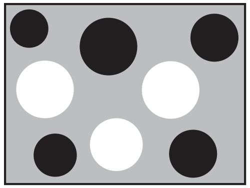
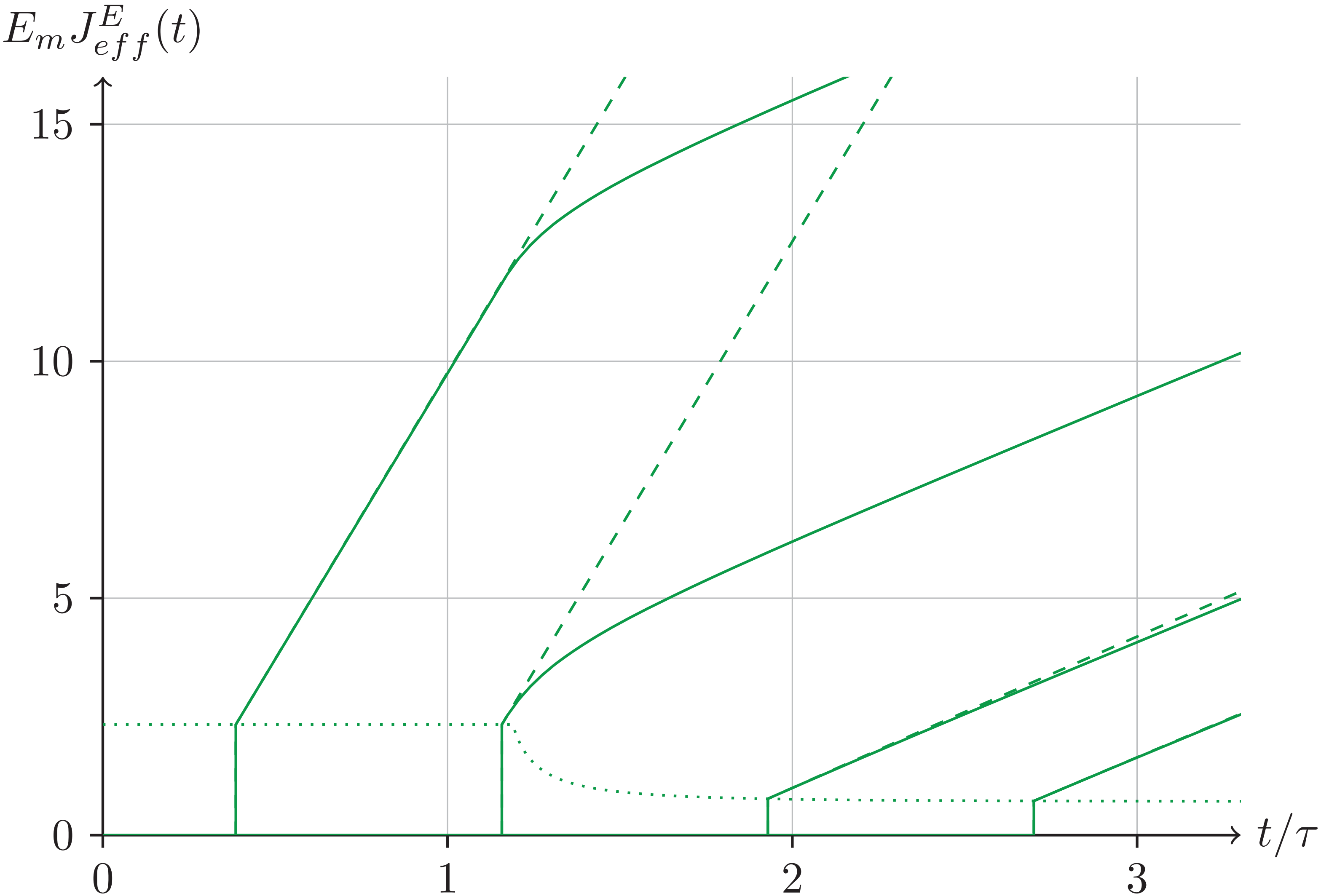
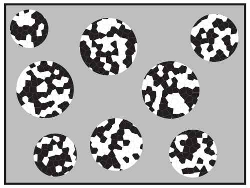




massive

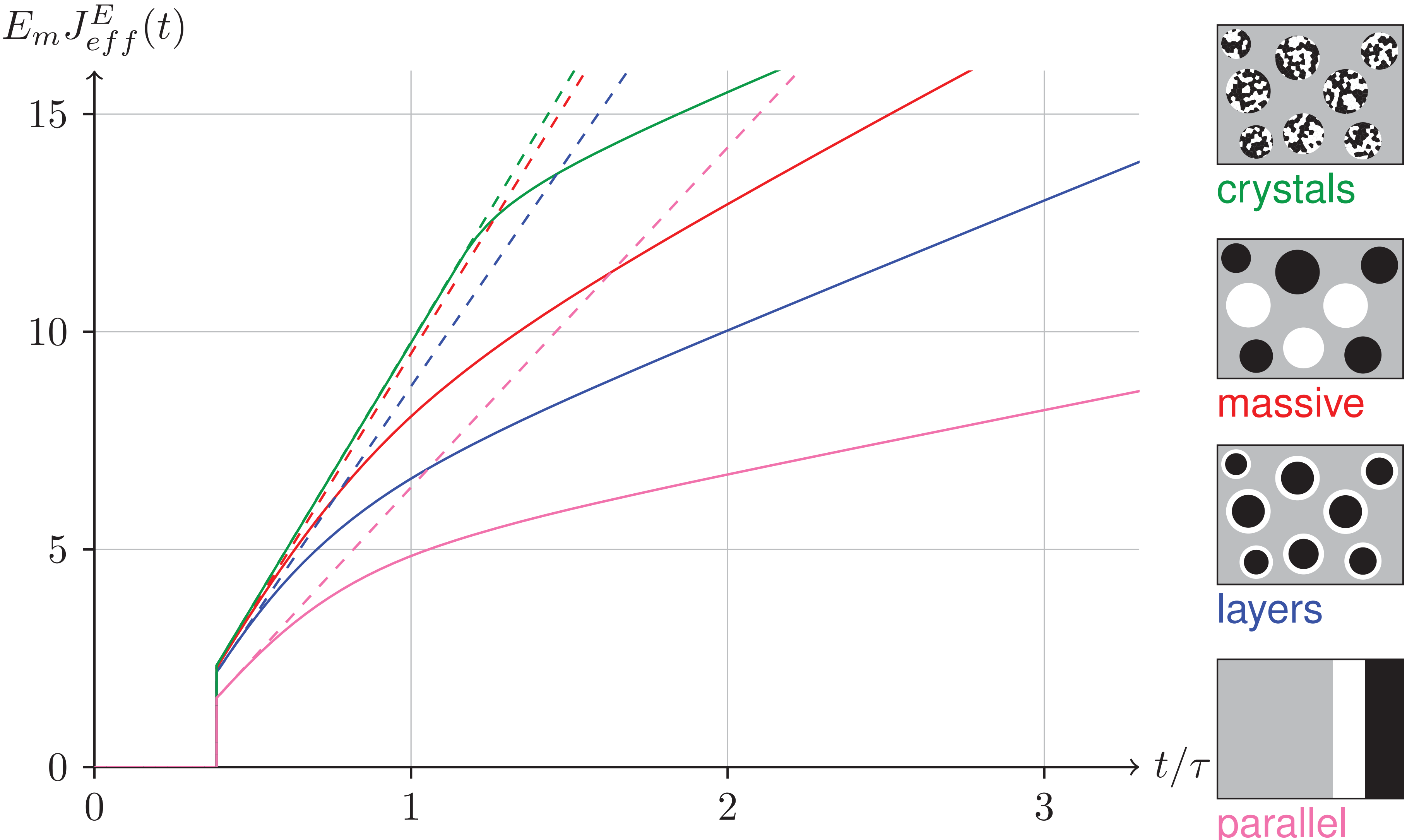
Results: effect of precipitation mechanism





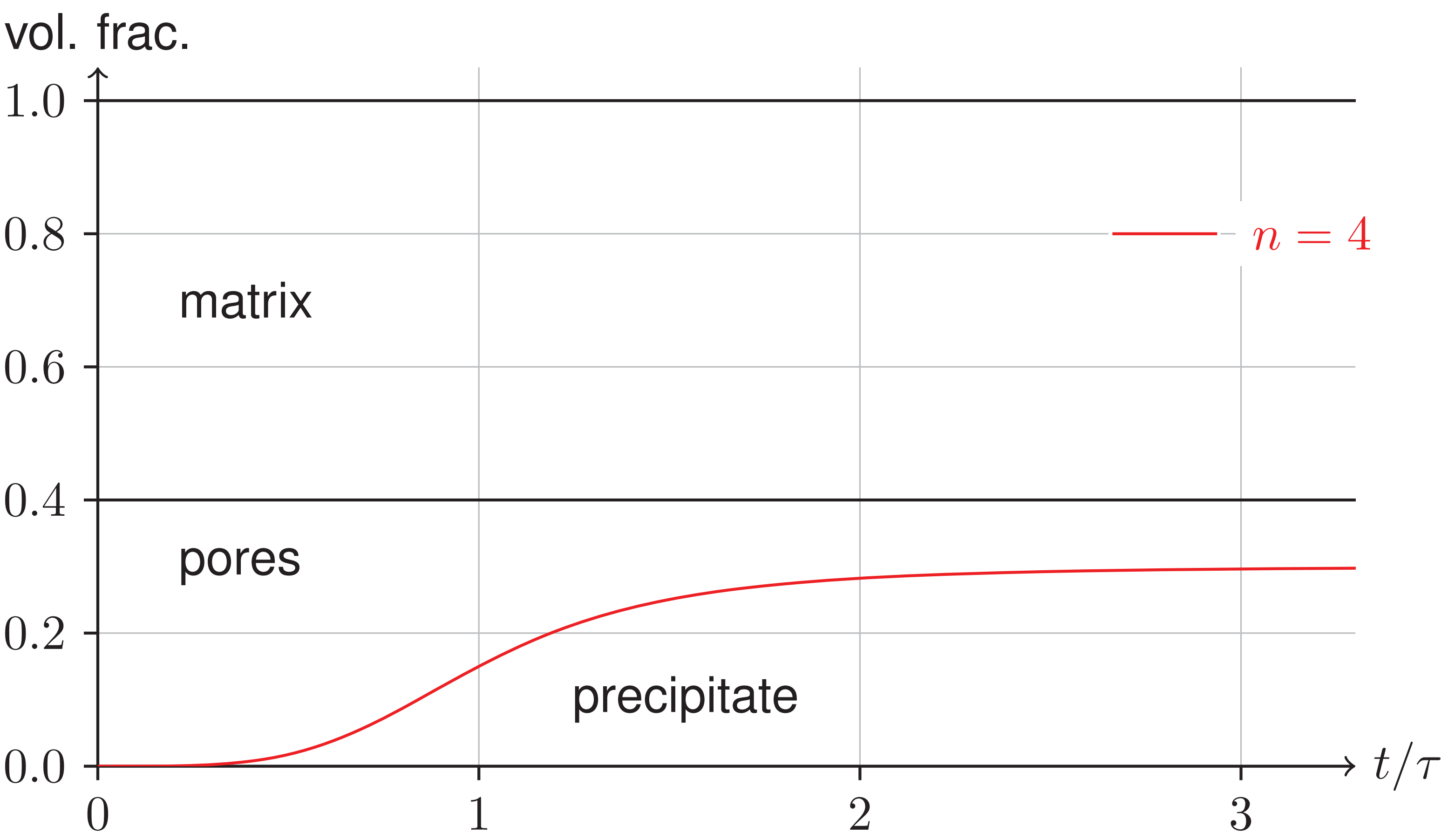
crystals

Results: effect of precipitation mechanism



Investigation of precipitation kinetics

$$f_{prec}(t) = f_{prec}^{\infty} \frac{(t/\tau)^n}{1 + (t/\tau)^n}$$



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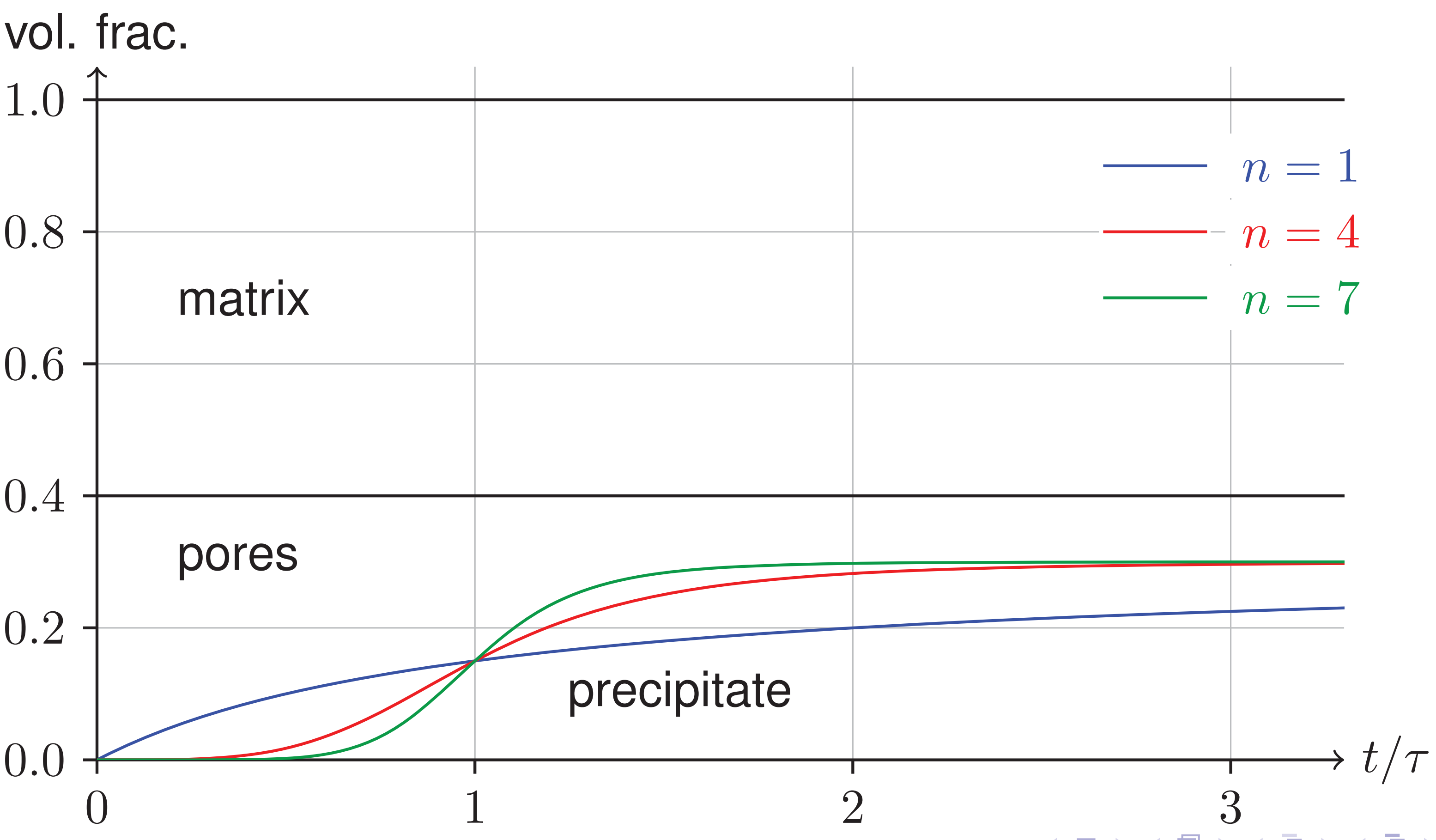
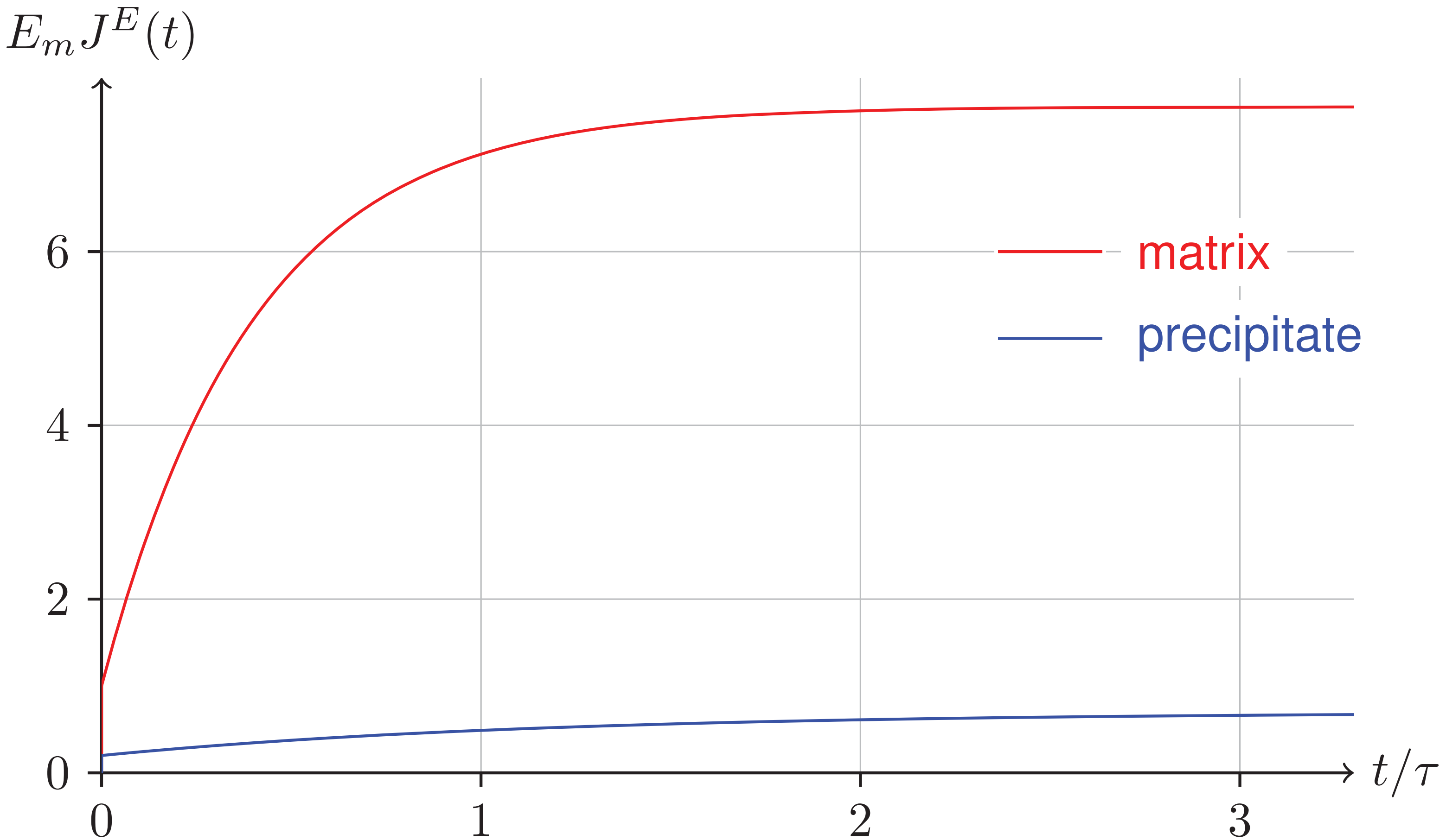
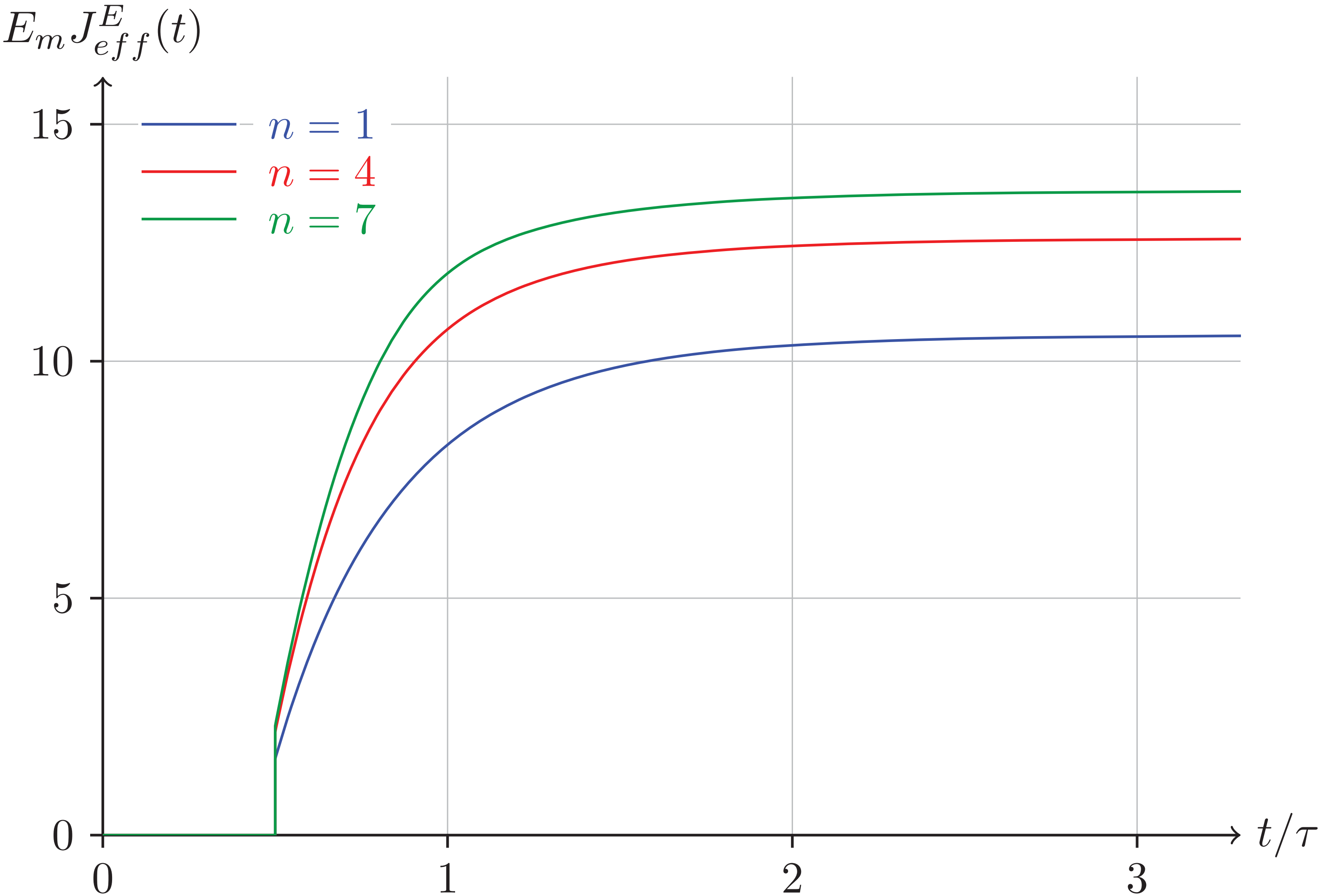


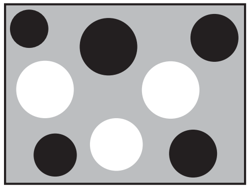
Matrix and precipitate behaviour

- isotropic non ageing linear viscoelastic
- constant Poisson ratio, Zener rheological model



Effect of precipitation kinetics: results





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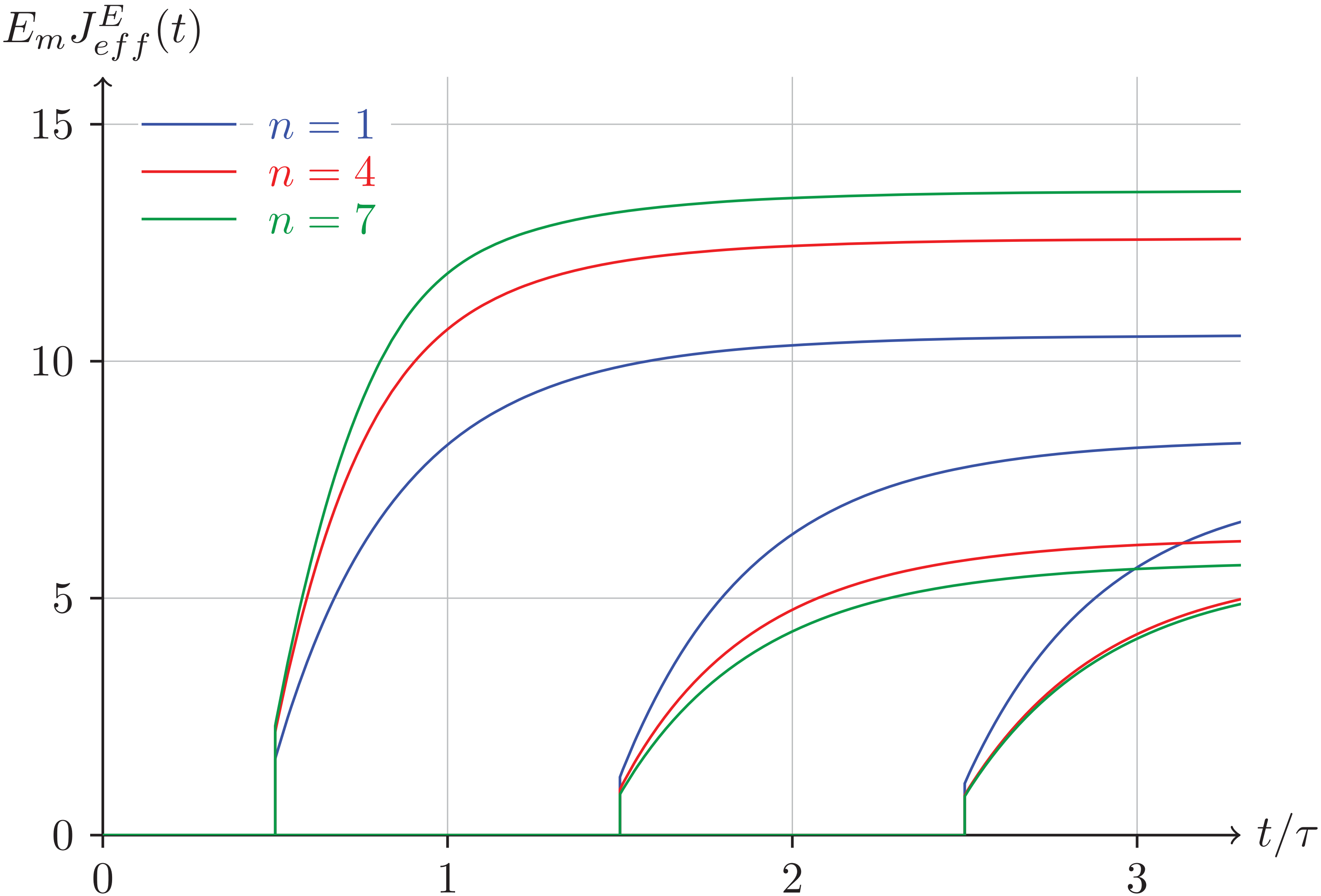
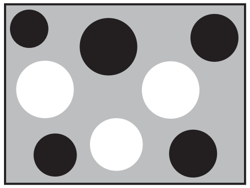
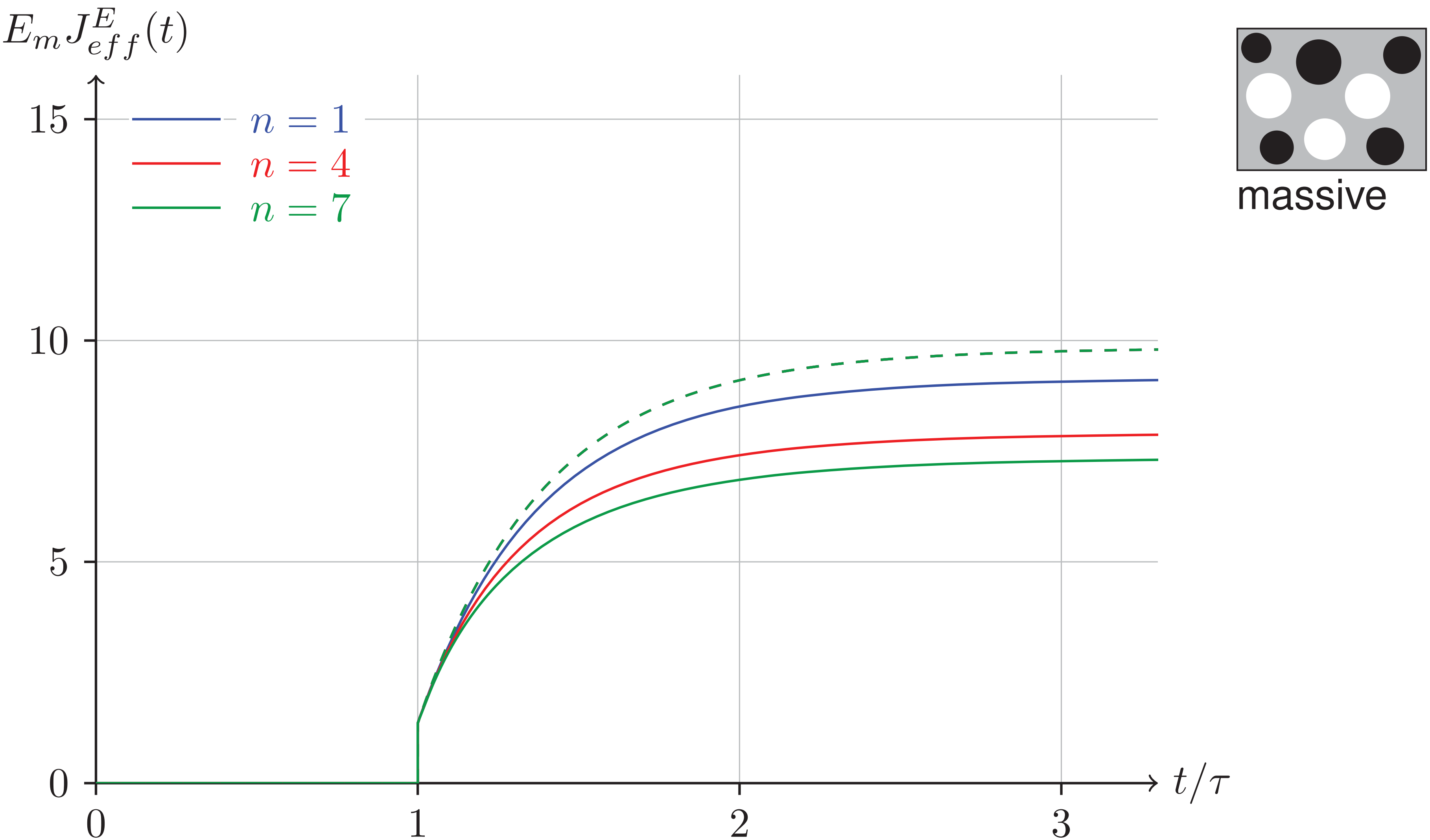




Effect of precipitation kinetics: results



Solidification theory: a micromechanical extension

"Frozen microstructure" is now history!

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Extension of Bažant solidification theory
+ ageing viscoelasticity homogenization → modular approach

- Non iterative nor incremental: manages the whole behaviour (full relaxation functions, time-sampled) at once
- Inputs can be improved independently
  - evolving morphological model
  - kinetics of phases volume fraction
  - elementary behaviours, any form: rheological model, analytical functions, samples (datapoints), lower scale homogenization, ...

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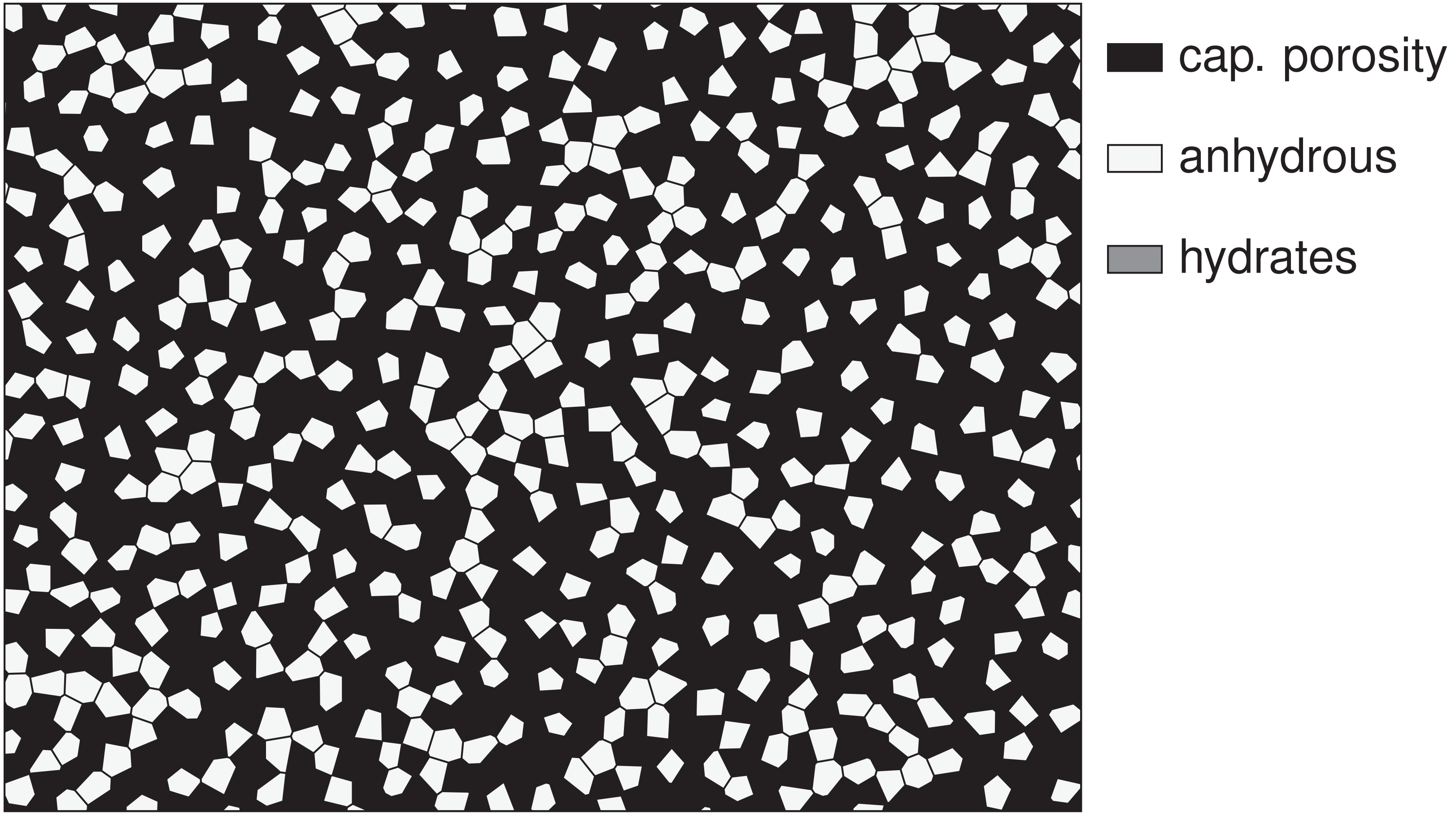
Approach mature enough to investigate cement paste

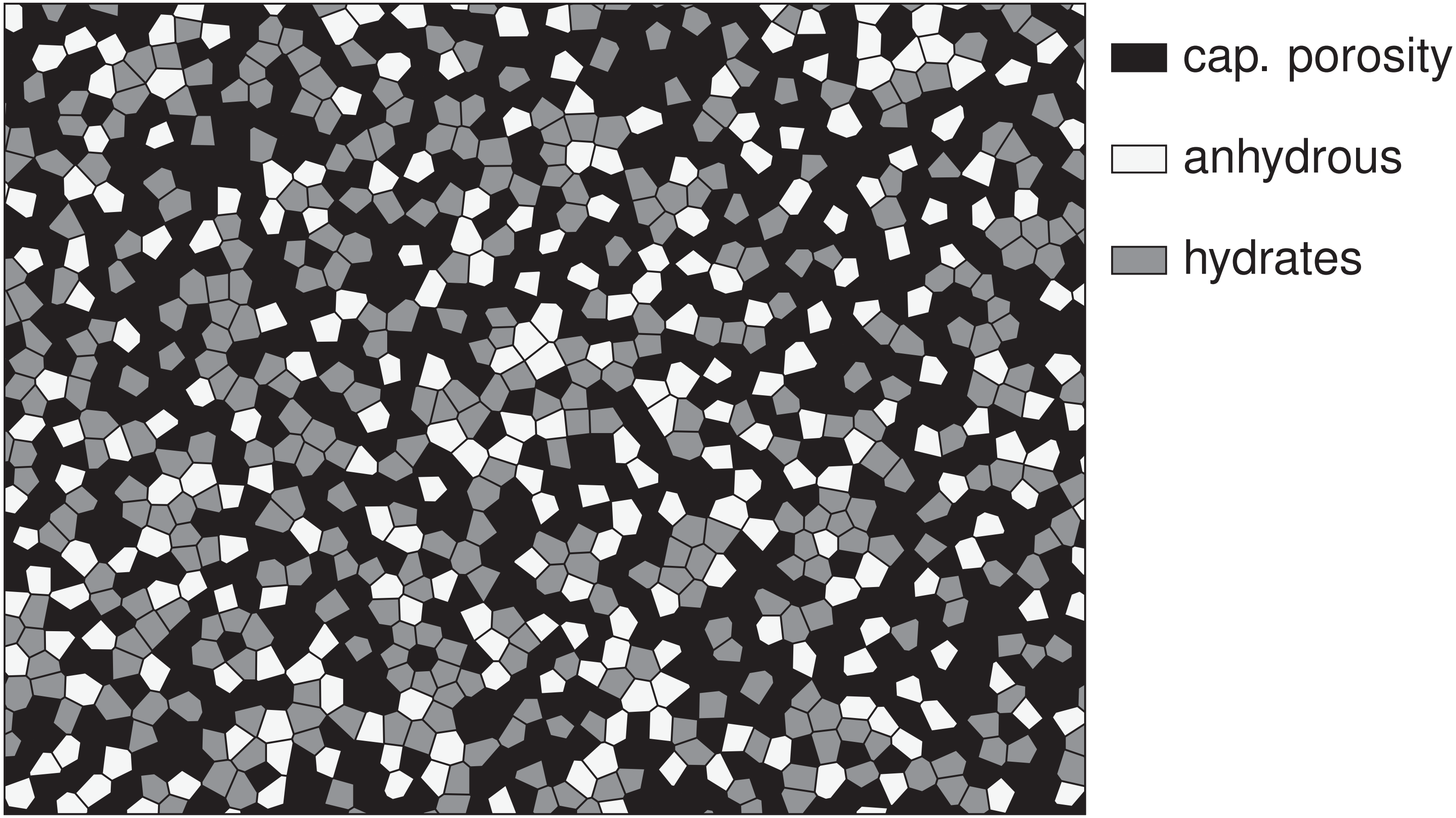
- only 3 phases: capillary pores, anhydrous, hydrates
- simplified microstructure evolution
- simplified hydration kinetics
- preliminary results

Towards cement paste: evolving microstructure



$w/c = 0.6$ $\alpha = 0$

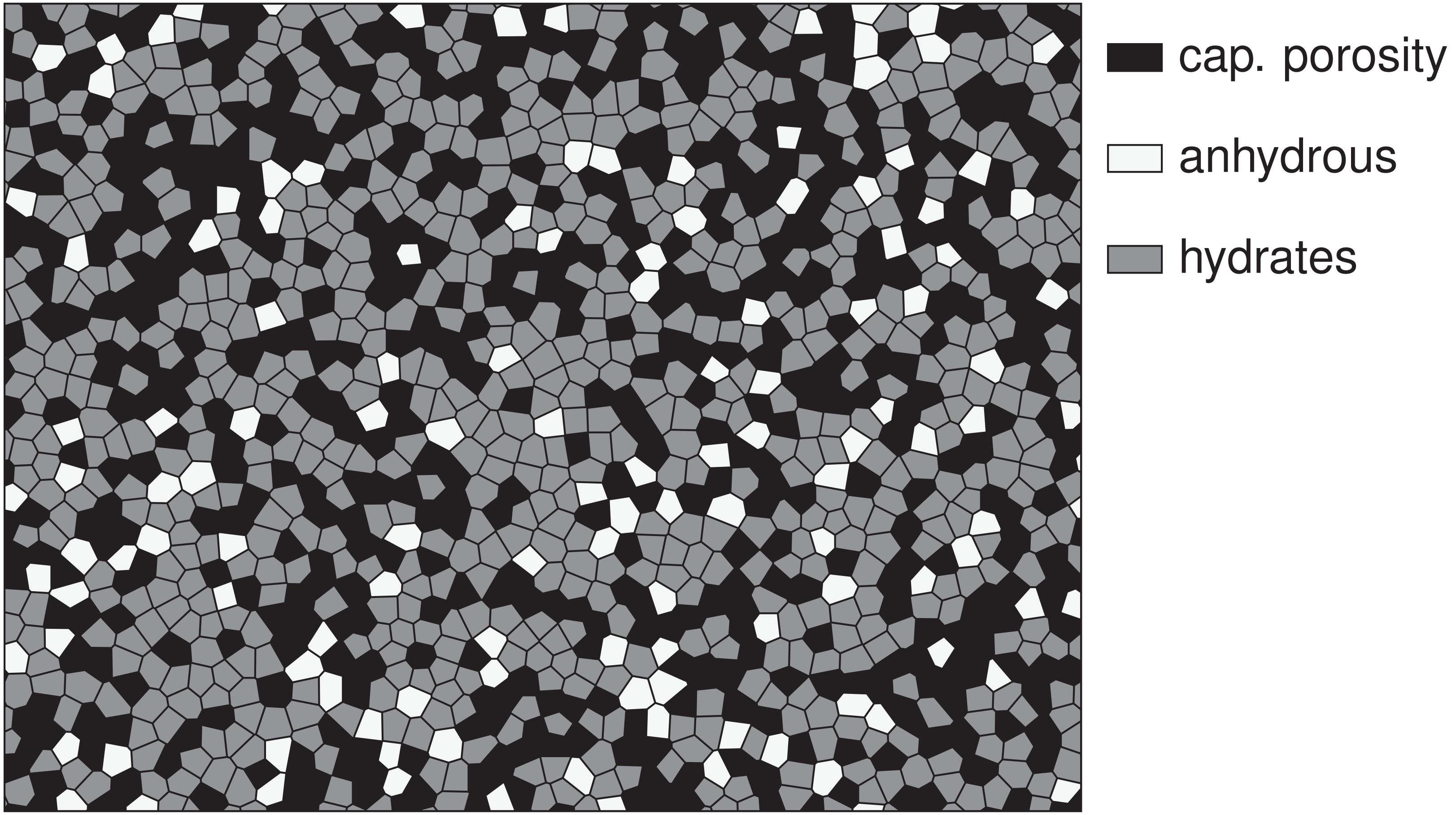
Towards cement paste: evolving microstructure



$w/c = 0.6$ $\alpha = 0.4$

precip. of hydrates + transf. anhydrous $\rightarrow$ hydrates

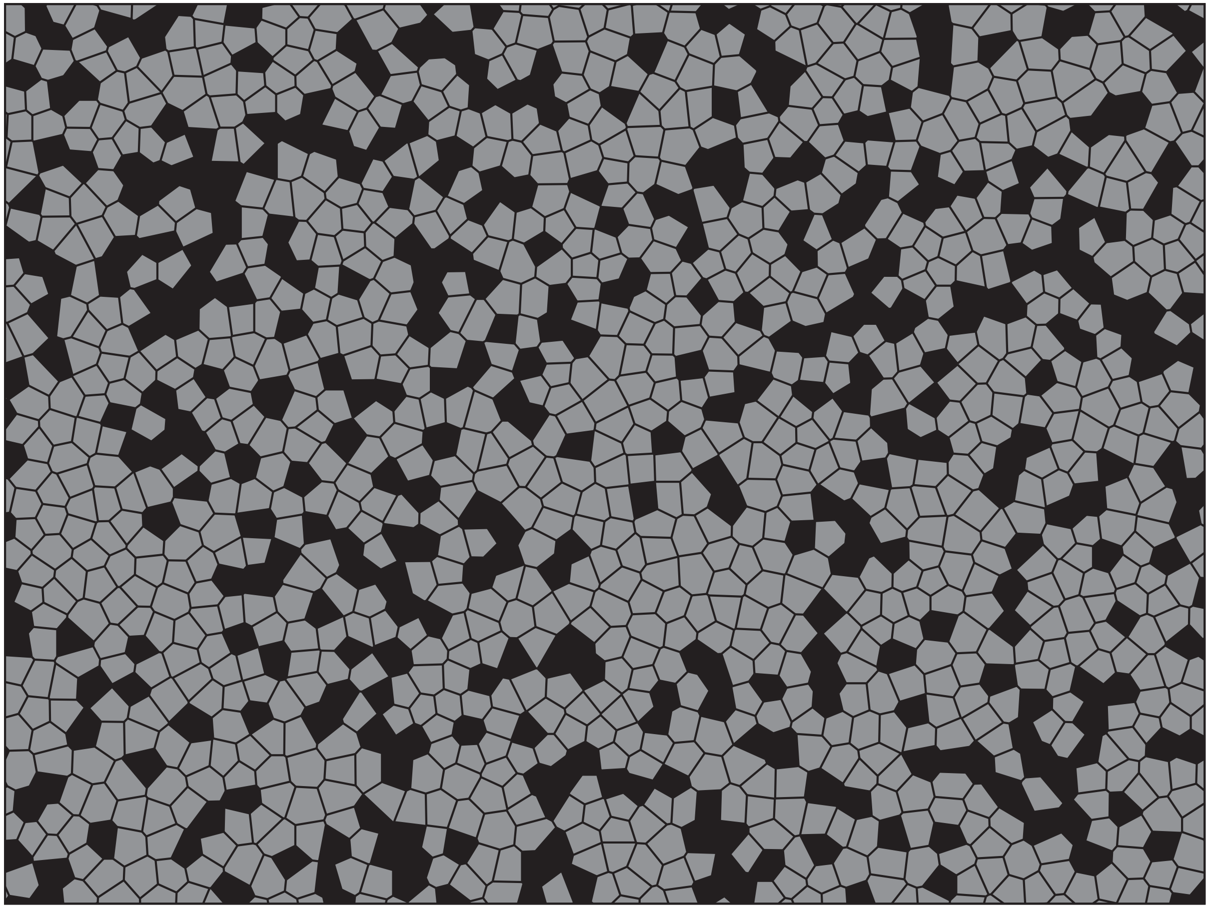
Towards cement paste: evolving microstructure



$w/c = 0.6$ $\alpha = 0.7$

precip. of hydrates + transf. anhydrous $\rightarrow$ hydrates

Towards cement paste: evolving microstructure



cap. porosity

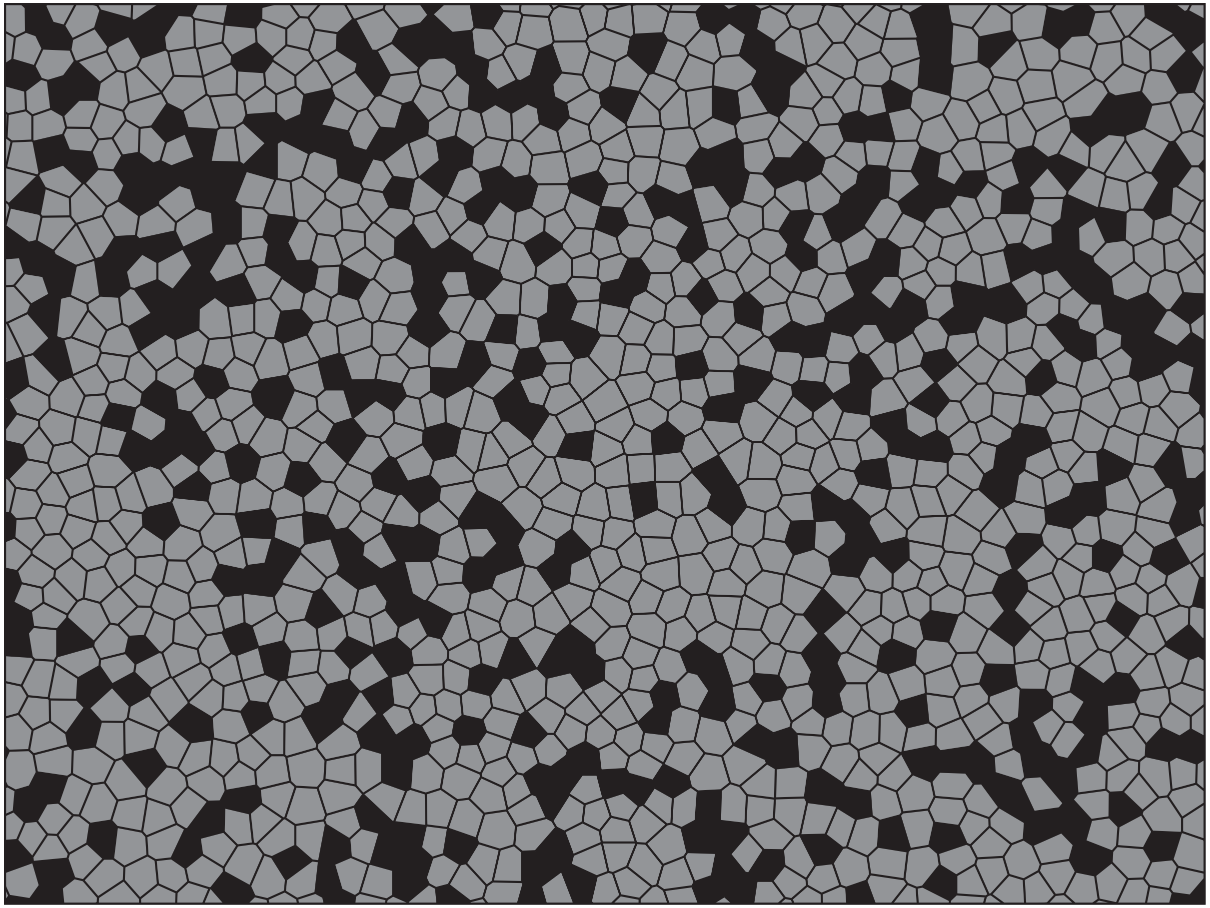
anhydrous

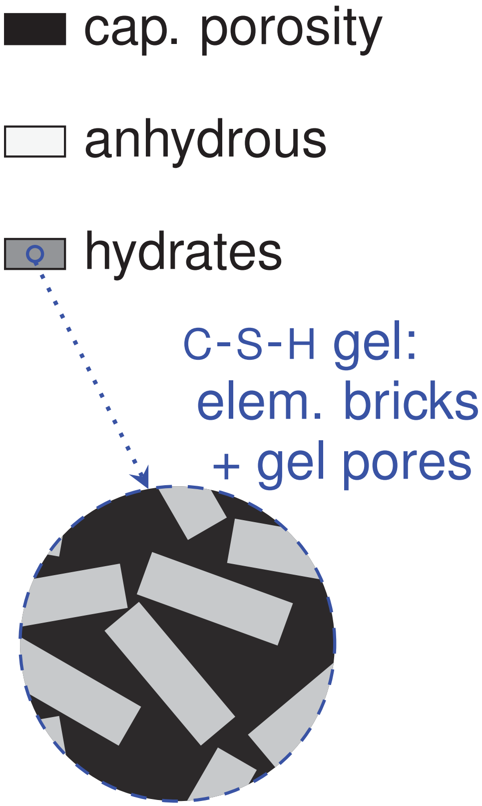
hydrates

$w/c = 0.6$ $\alpha = 1$

precip. of hydrates + transf. anhydrous $\rightarrow$ hydrates

Towards cement paste: evolving microstructure





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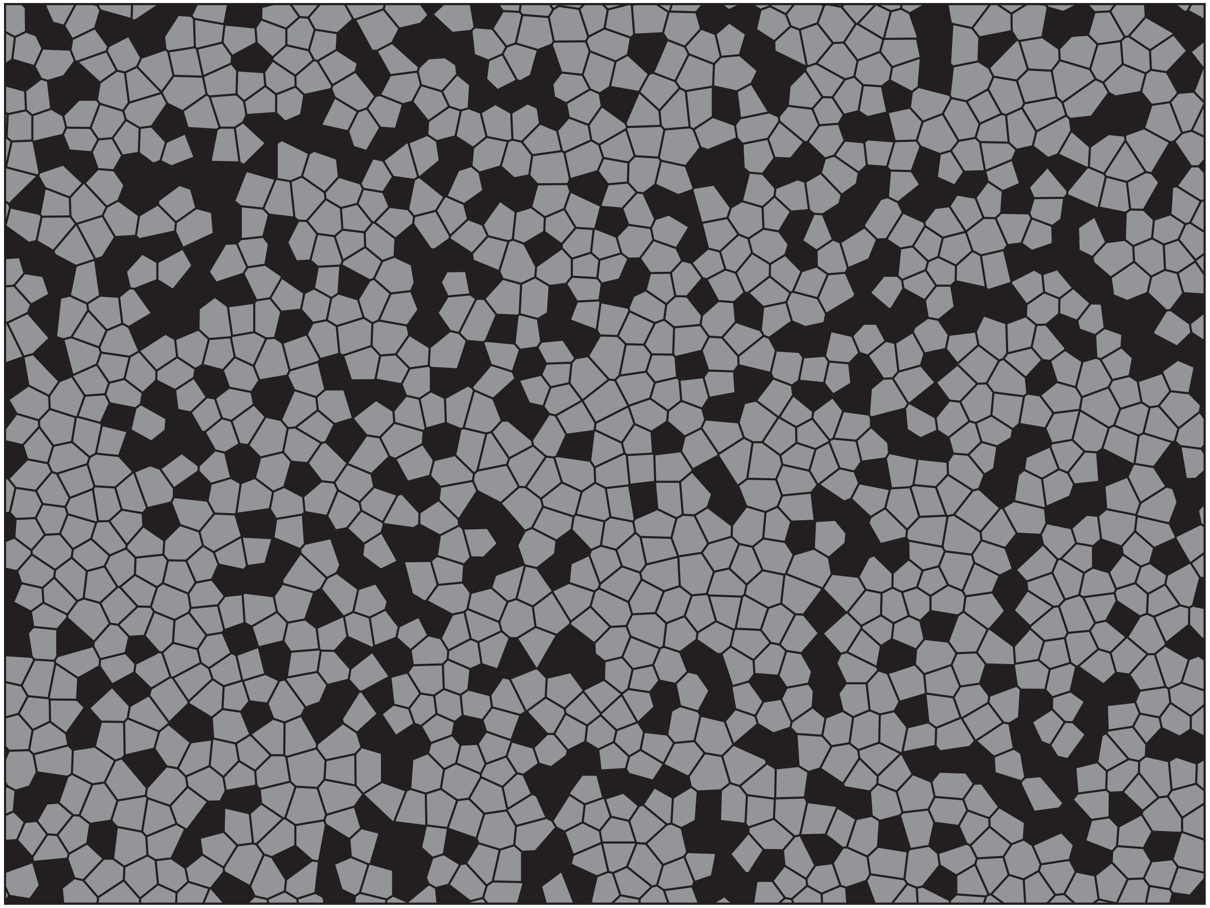
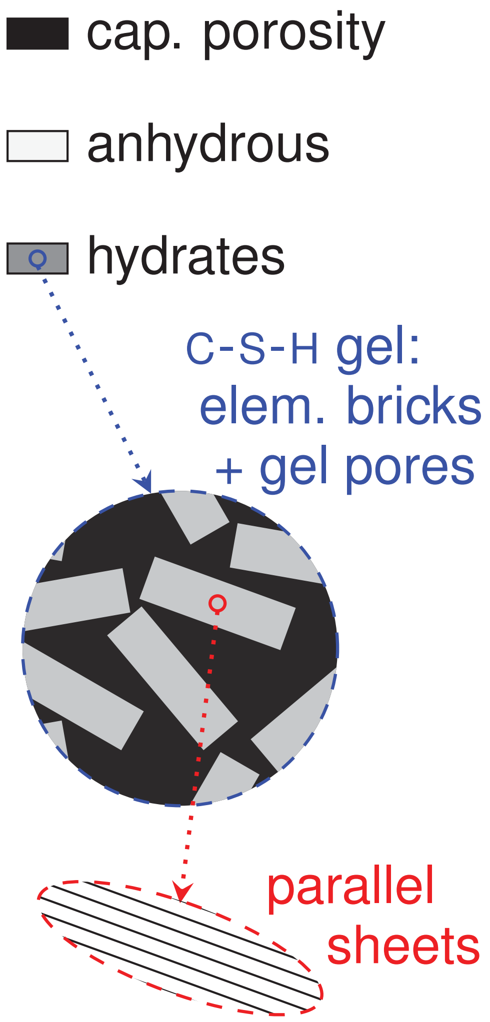




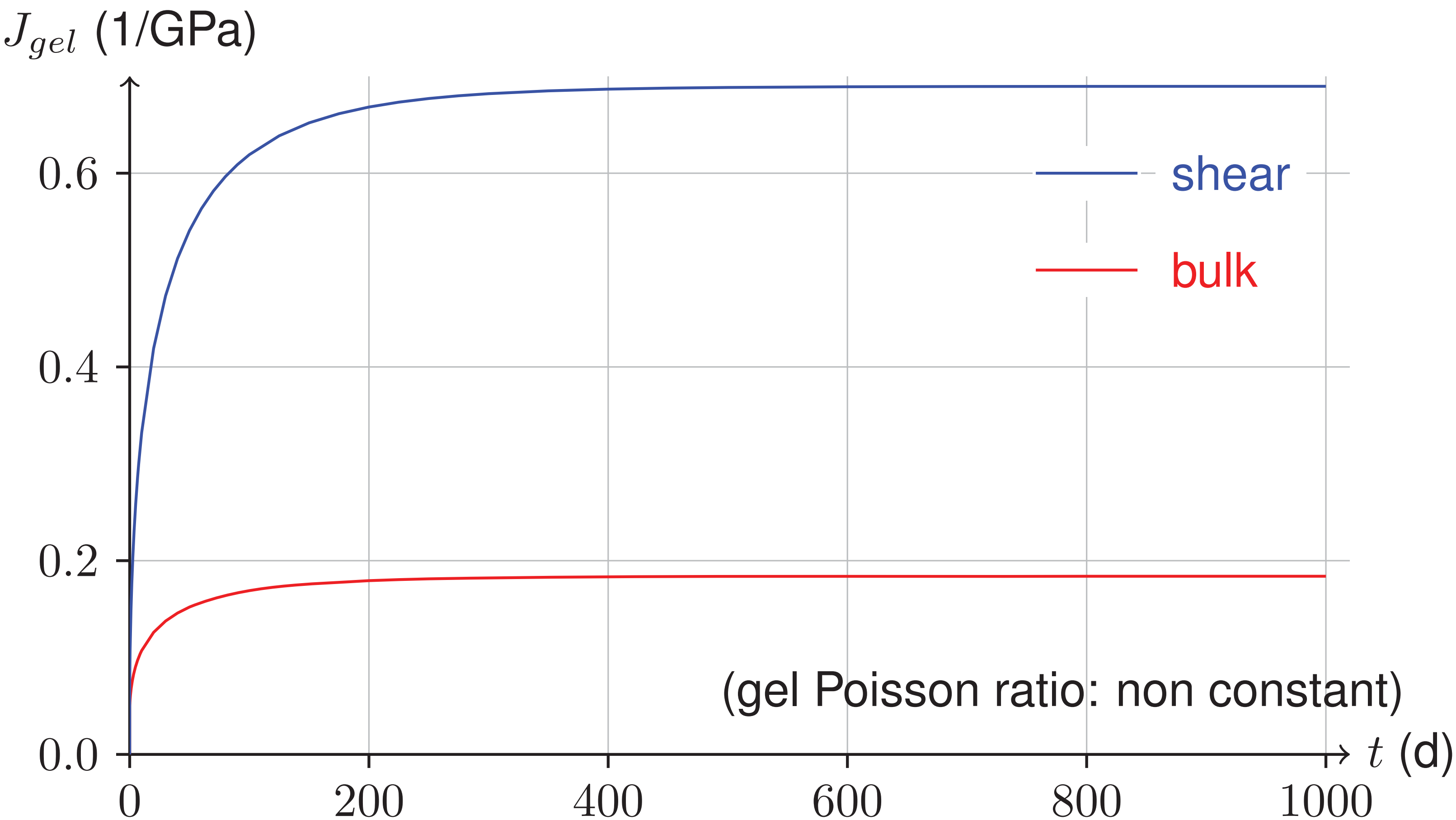
$w/c = 0.6 \qquad \alpha = 1$

precip. of hydrates + transf. anhydrous $\rightarrow$ hydrates

C-S-H gel: non ageing creep

brick: isotropic elastic + viscous sliding of sheets (Maxwell, $\tau = 1.6$ h)

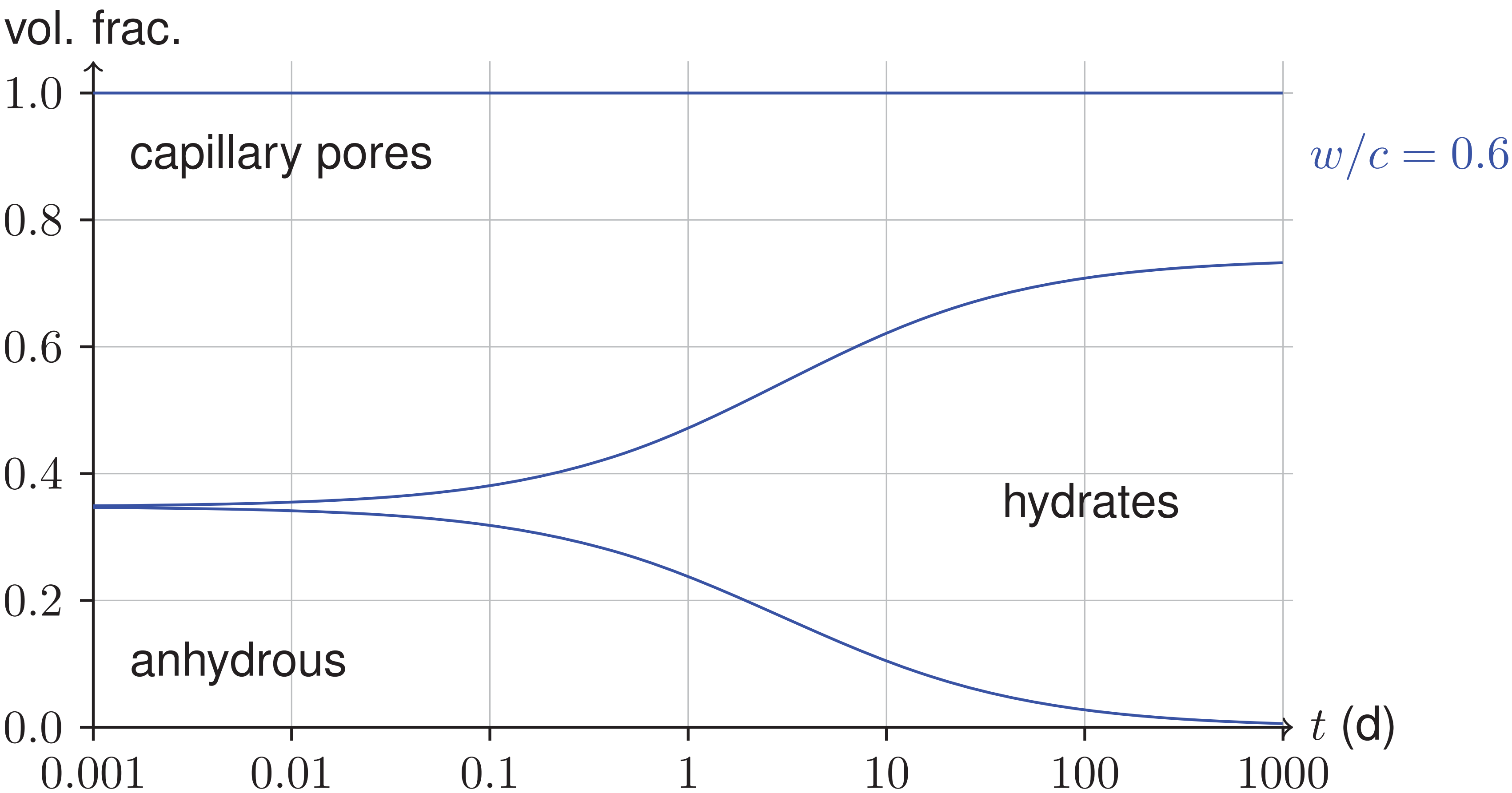
C-S-H gel: bricks + gel pores ($\varphi_{gel} = 0.3$)



[J. SANAHUJA, L. DORMIEUX. *Creep of a* C-S-H *gel: micromechanical approach.* IJMCE 8 (2010)]

Simplified hydration kinetics

Powers model + simplified kinetics: $\alpha(t) = \alpha^{\infty} \frac{(t/\tau)^n}{1+(t/\tau)^n}$, $\tau = 3$ d, $n = 0.7$



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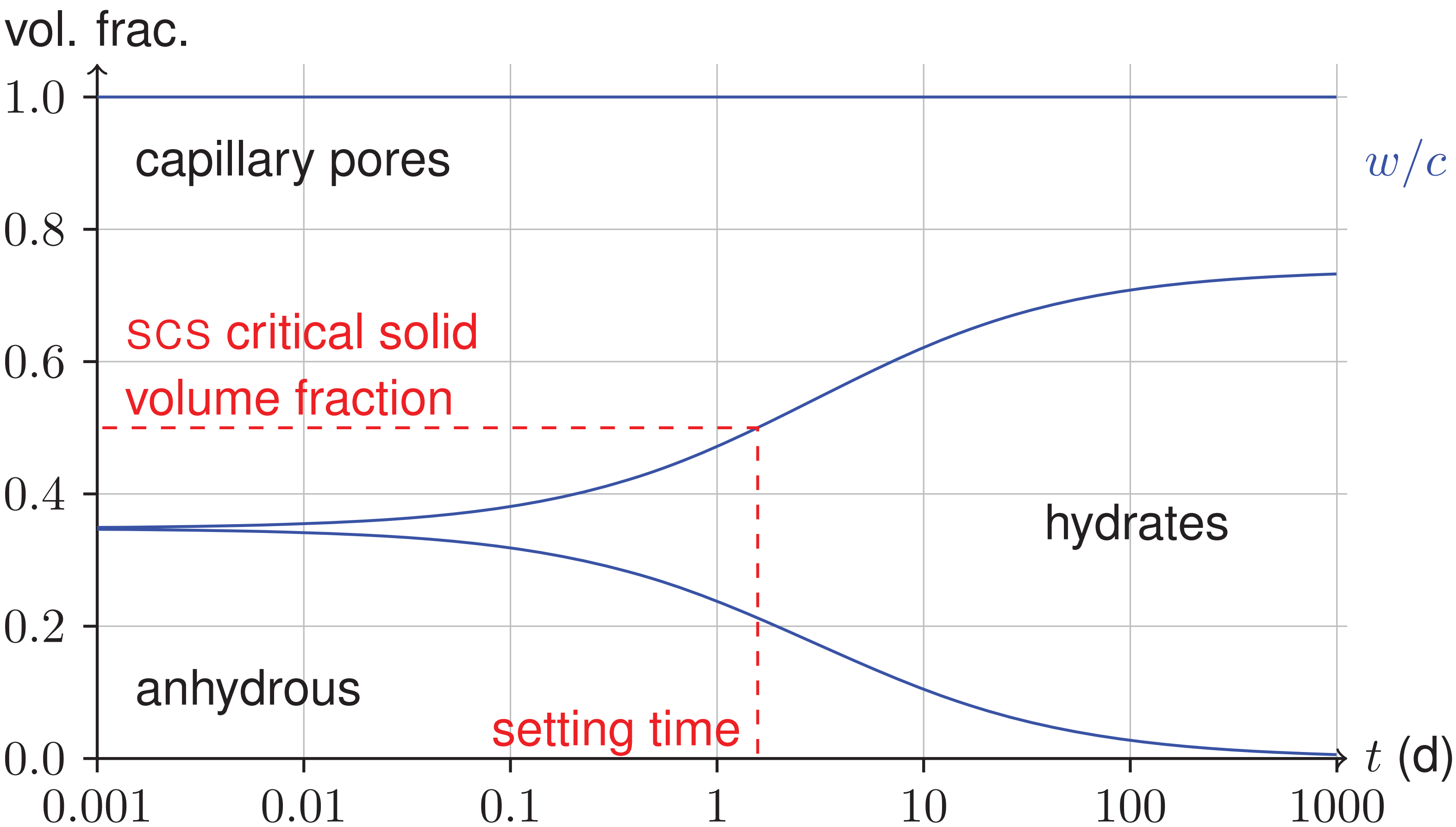
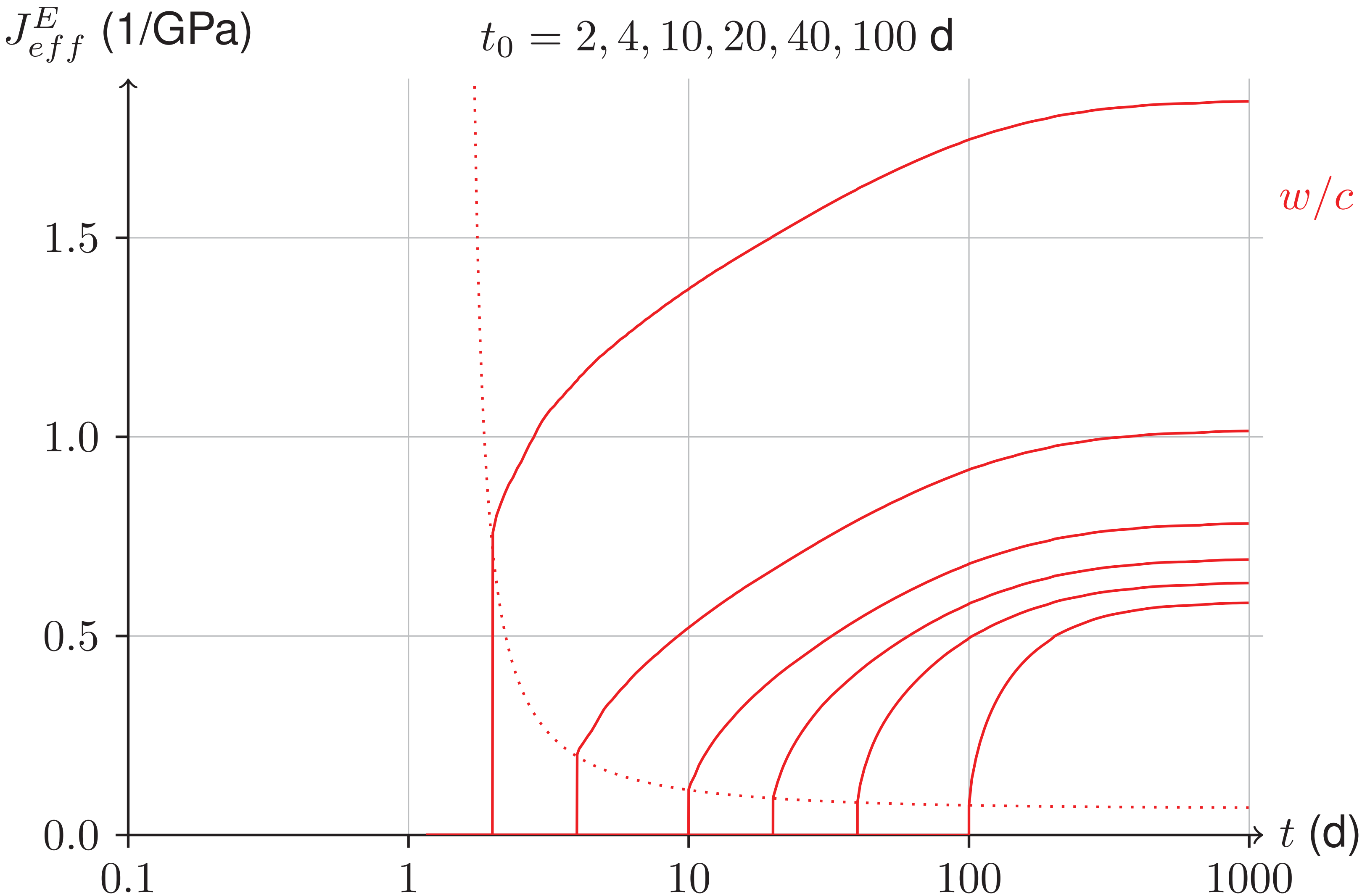


Effective uniaxial creep of cement paste



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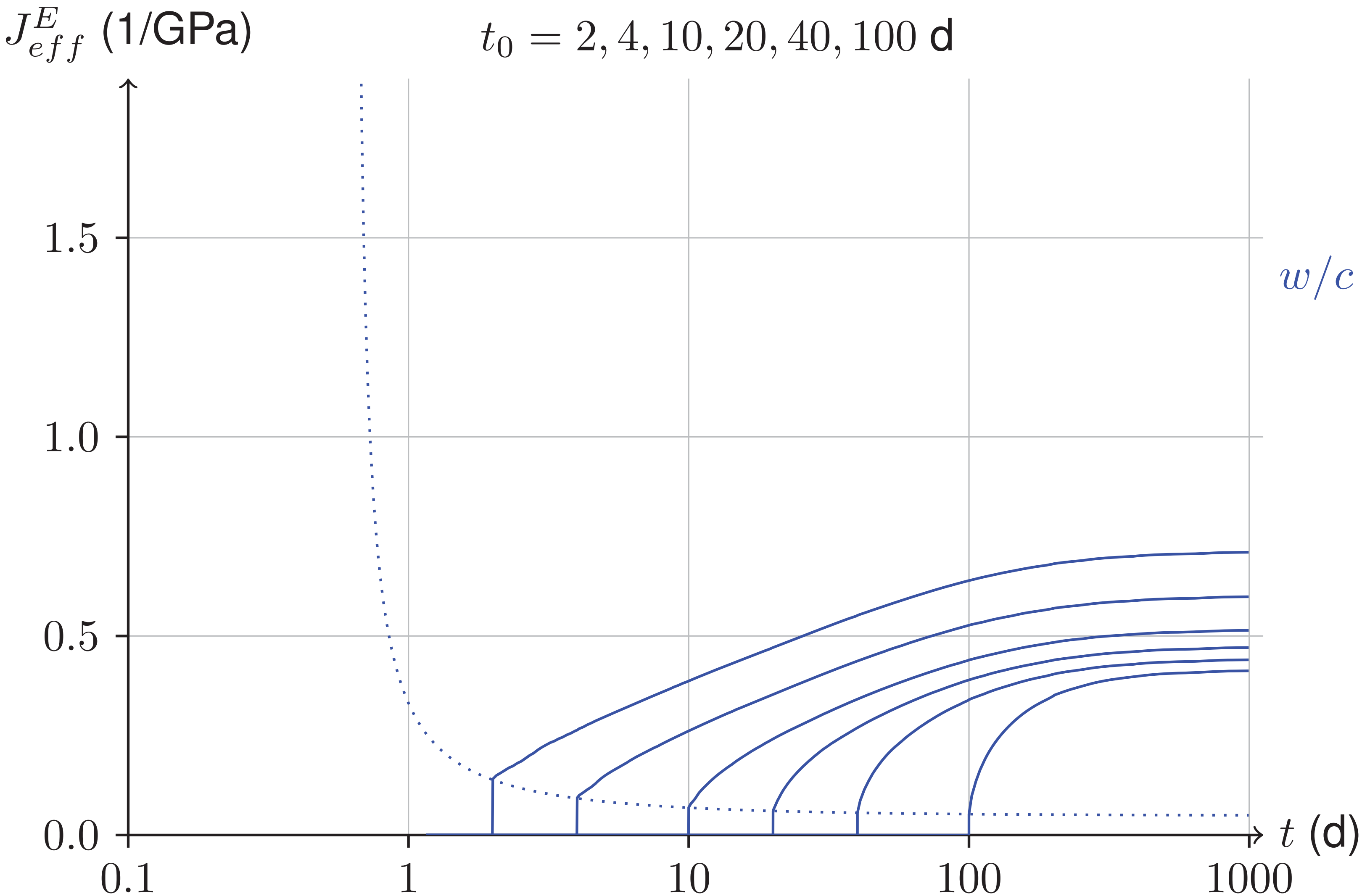

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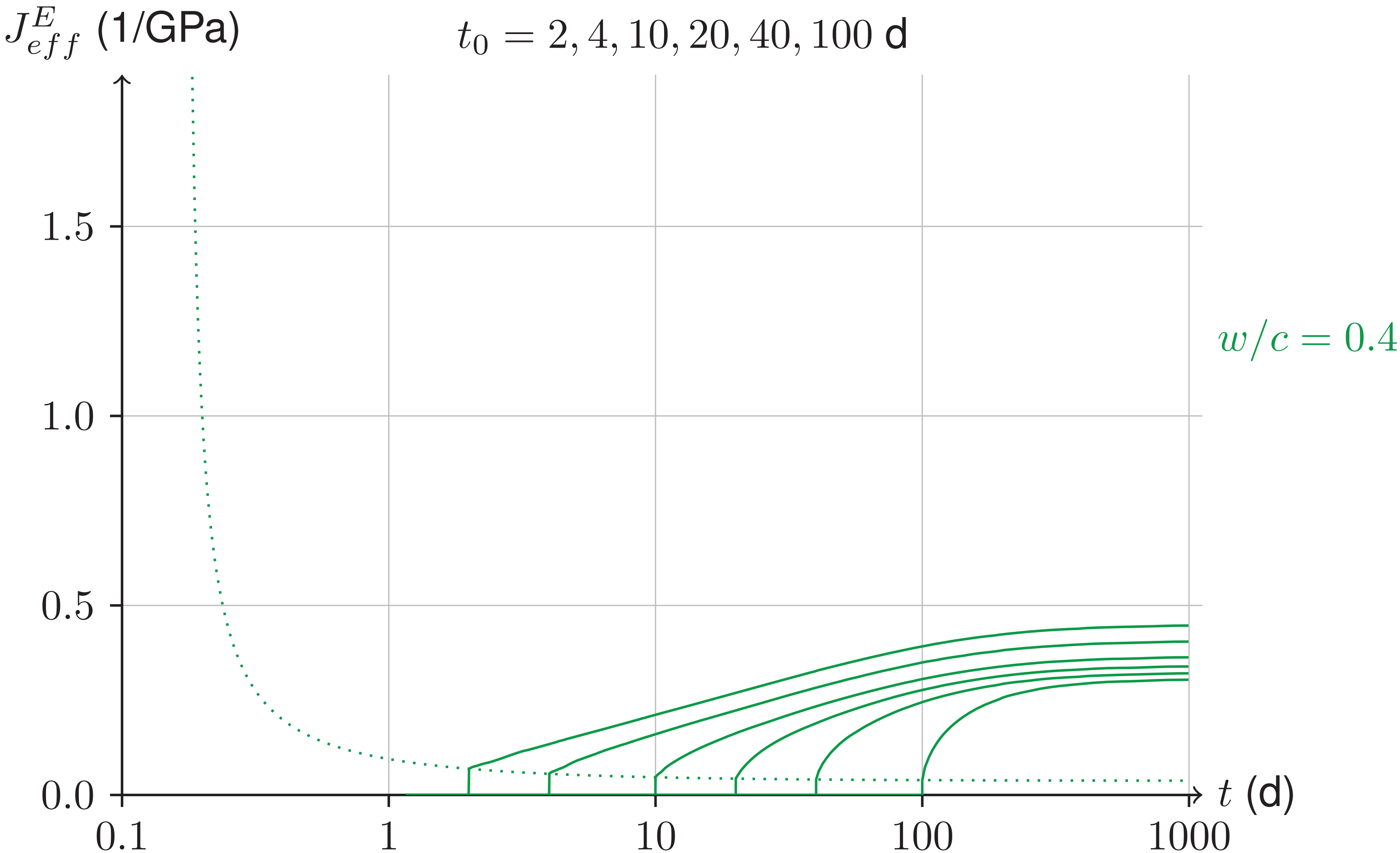

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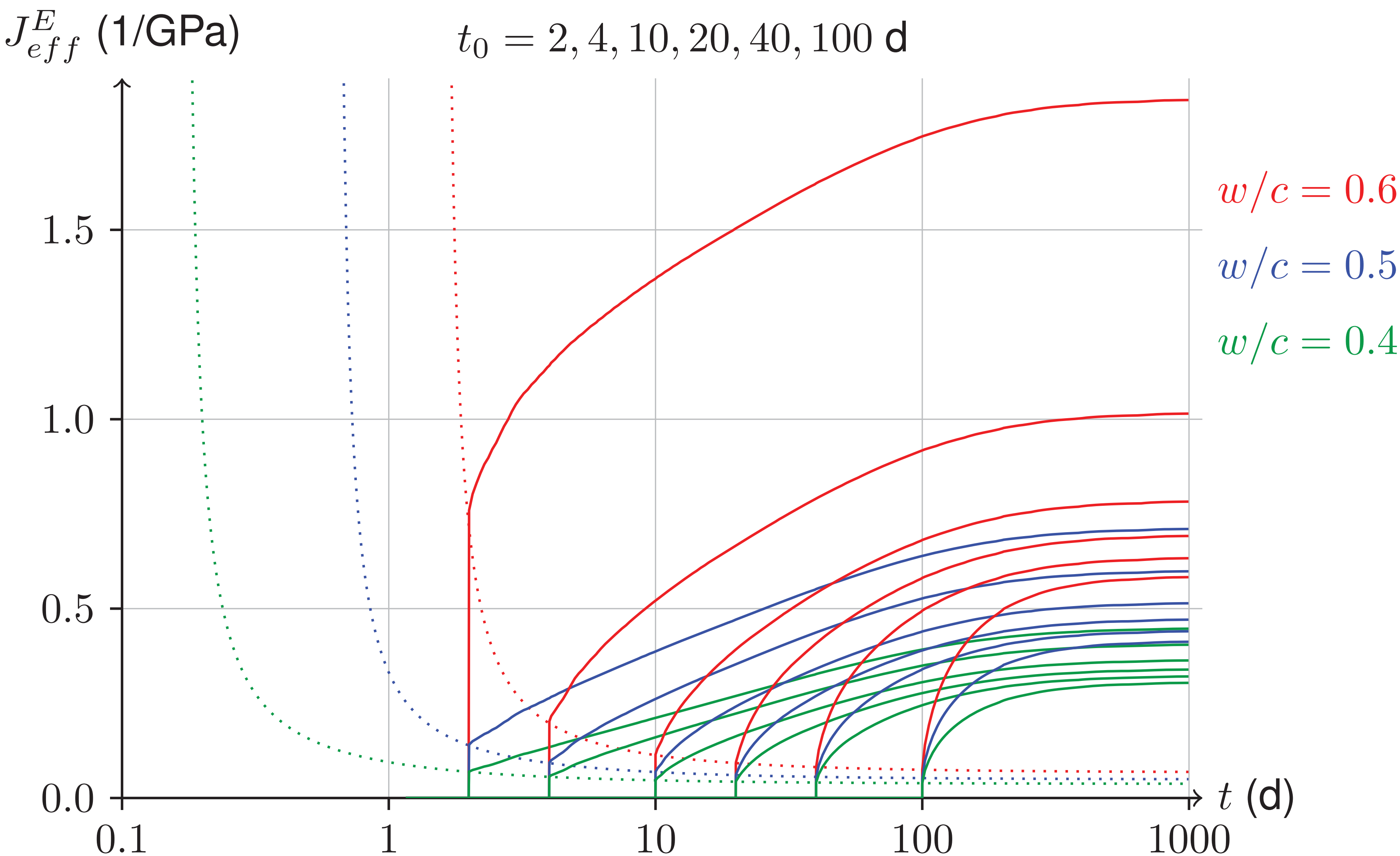
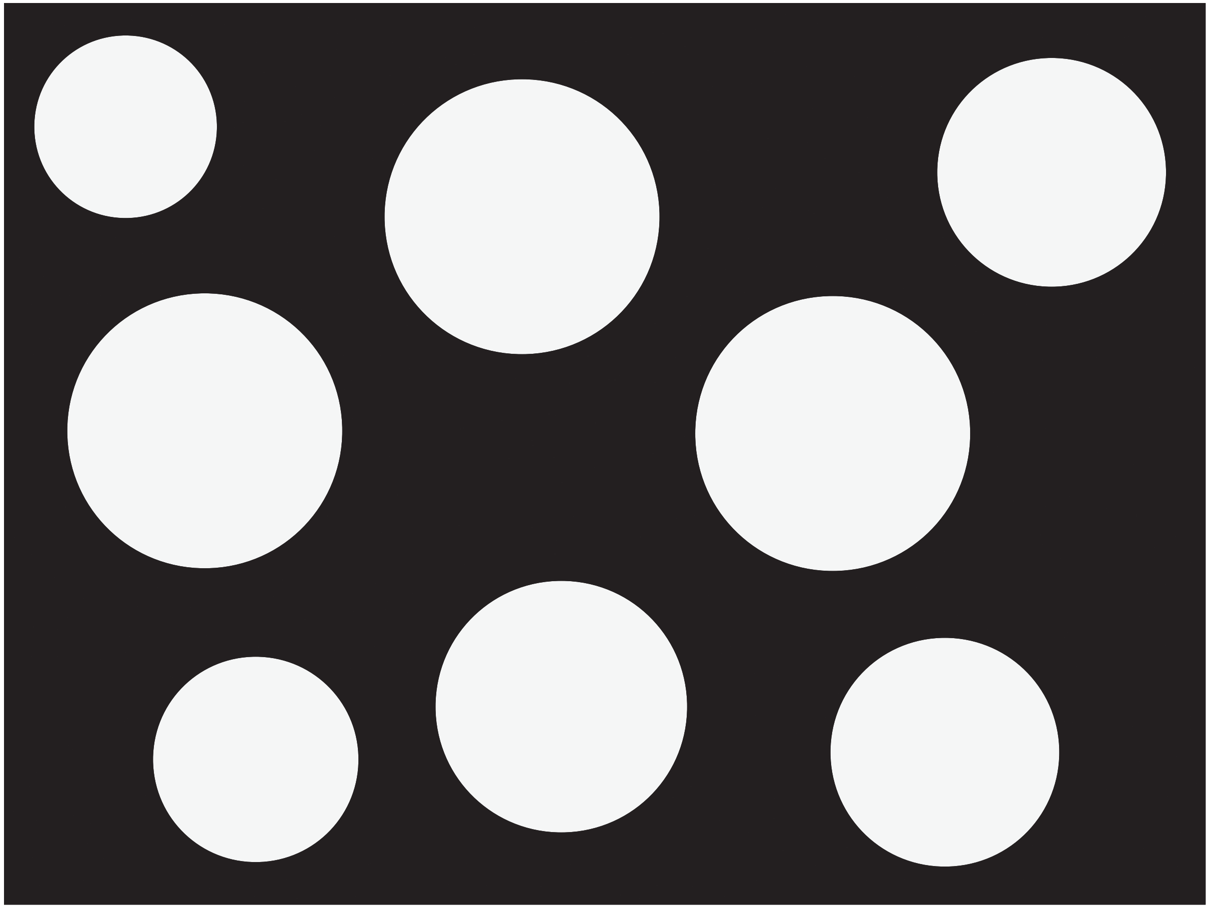
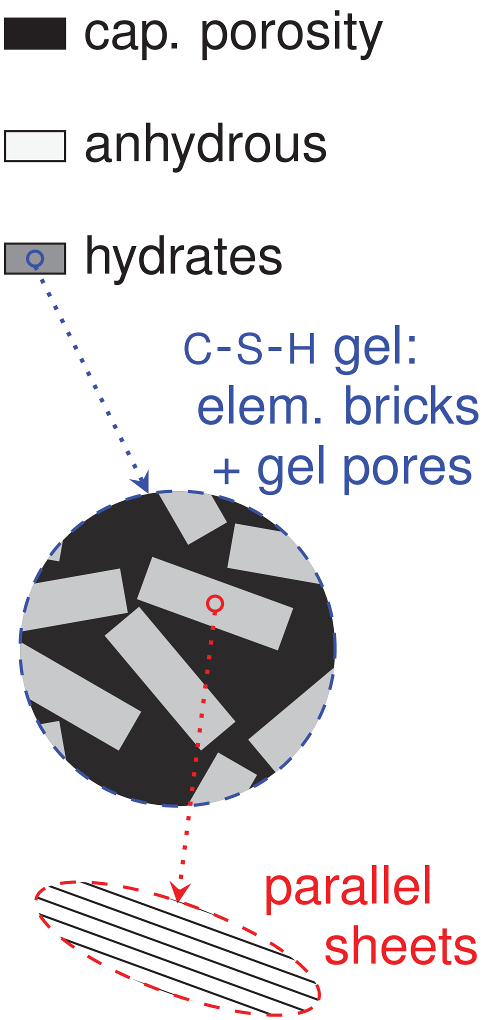


A more realistic cement paste evolving microstructure





$w/c = 0.6$ $\alpha = 0$

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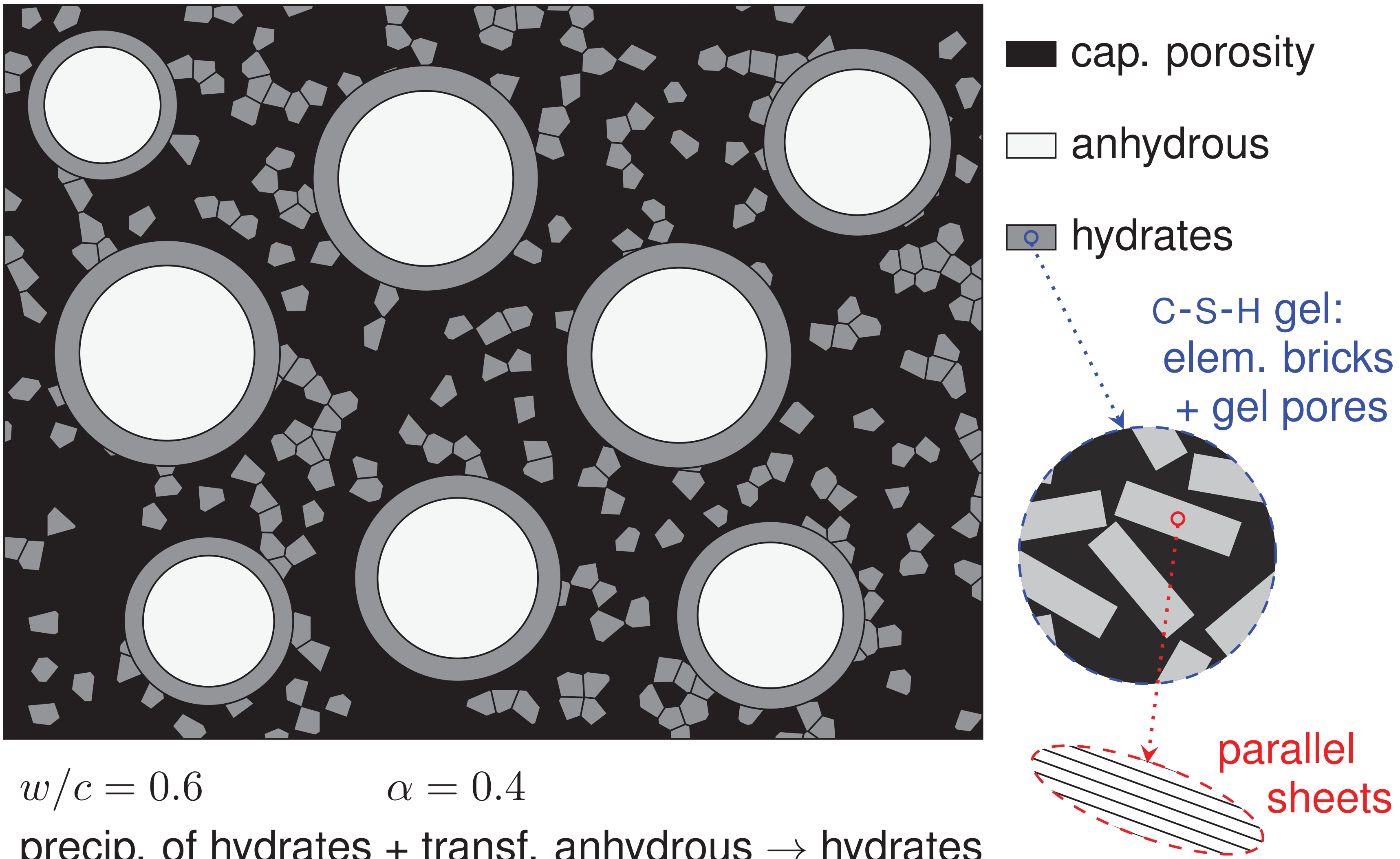

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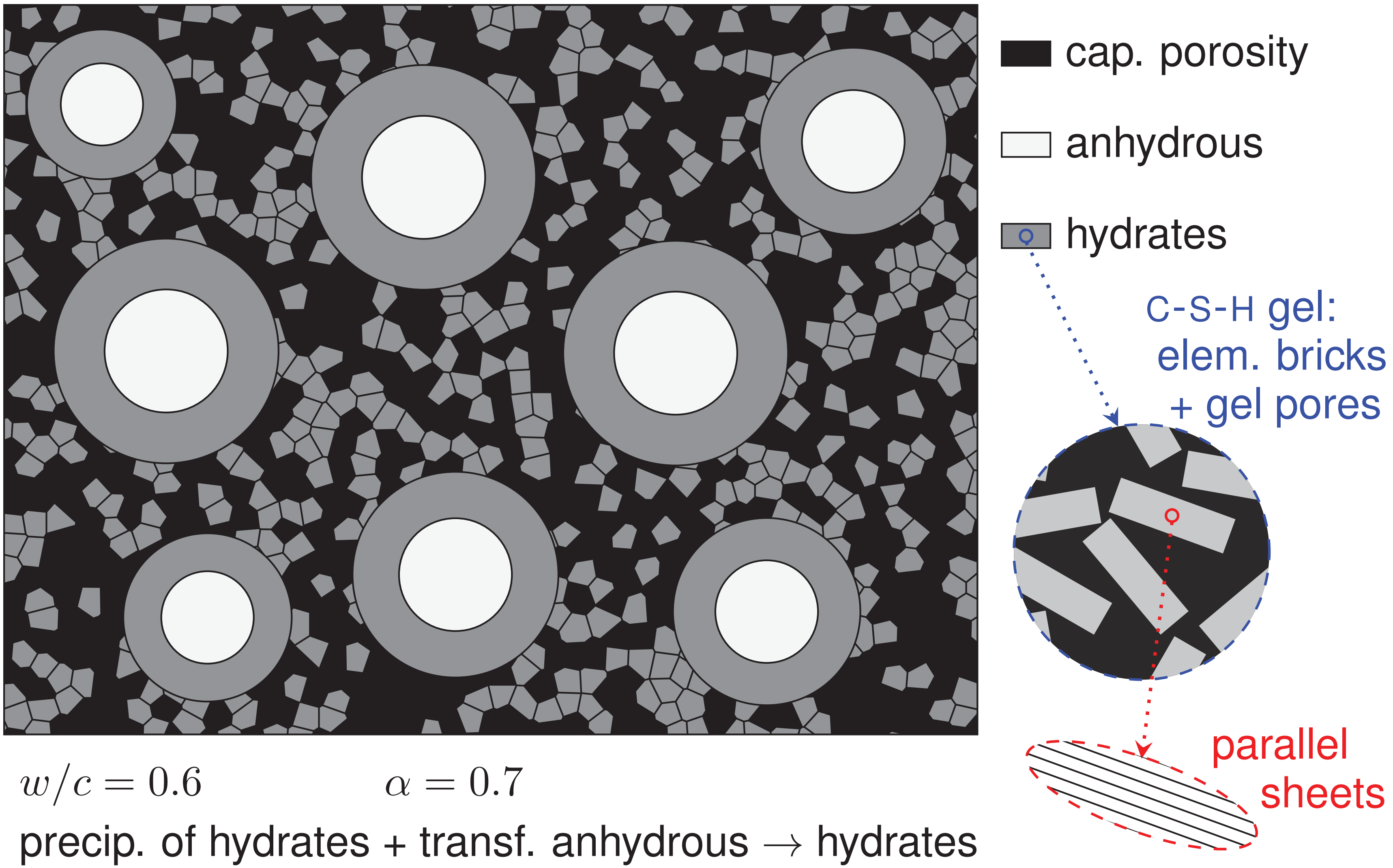

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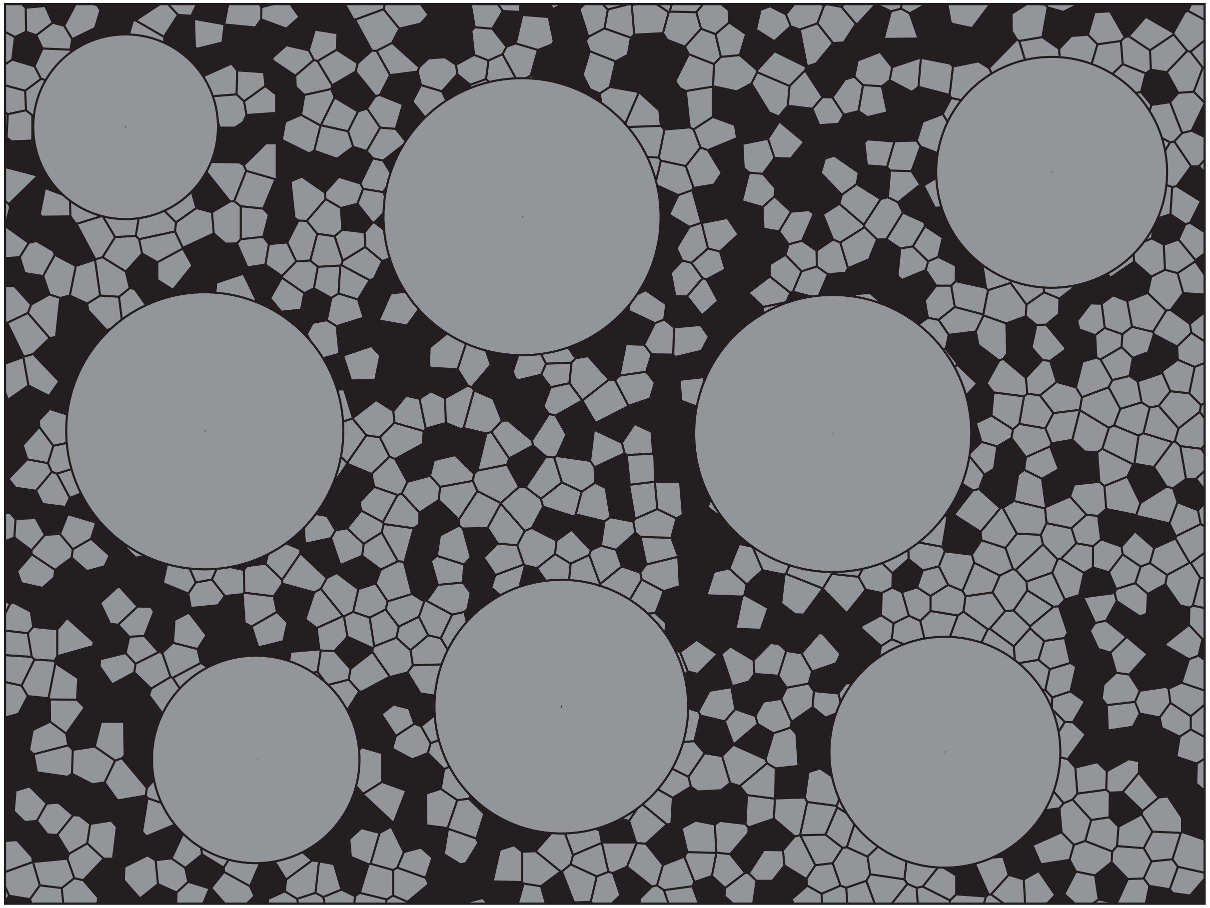

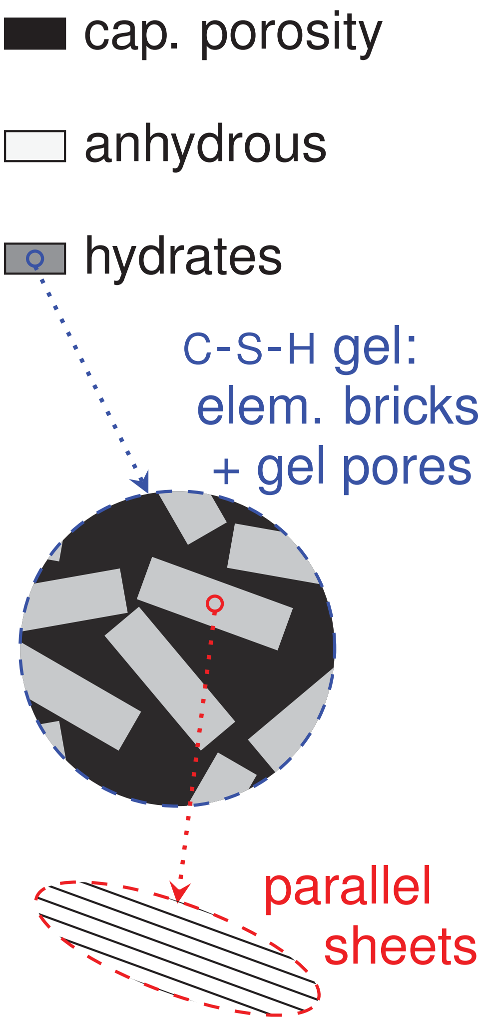

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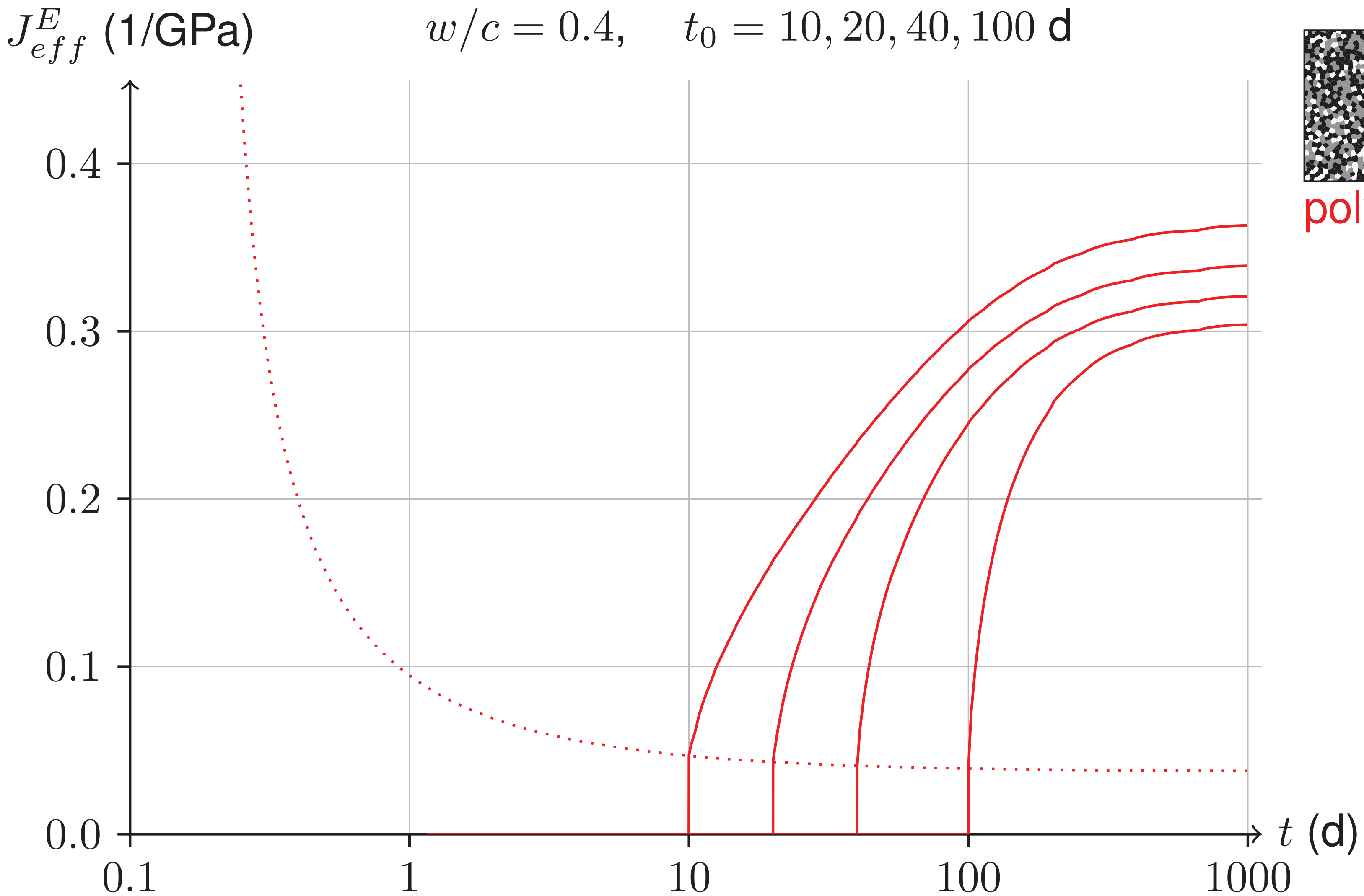
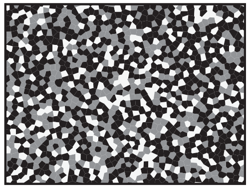
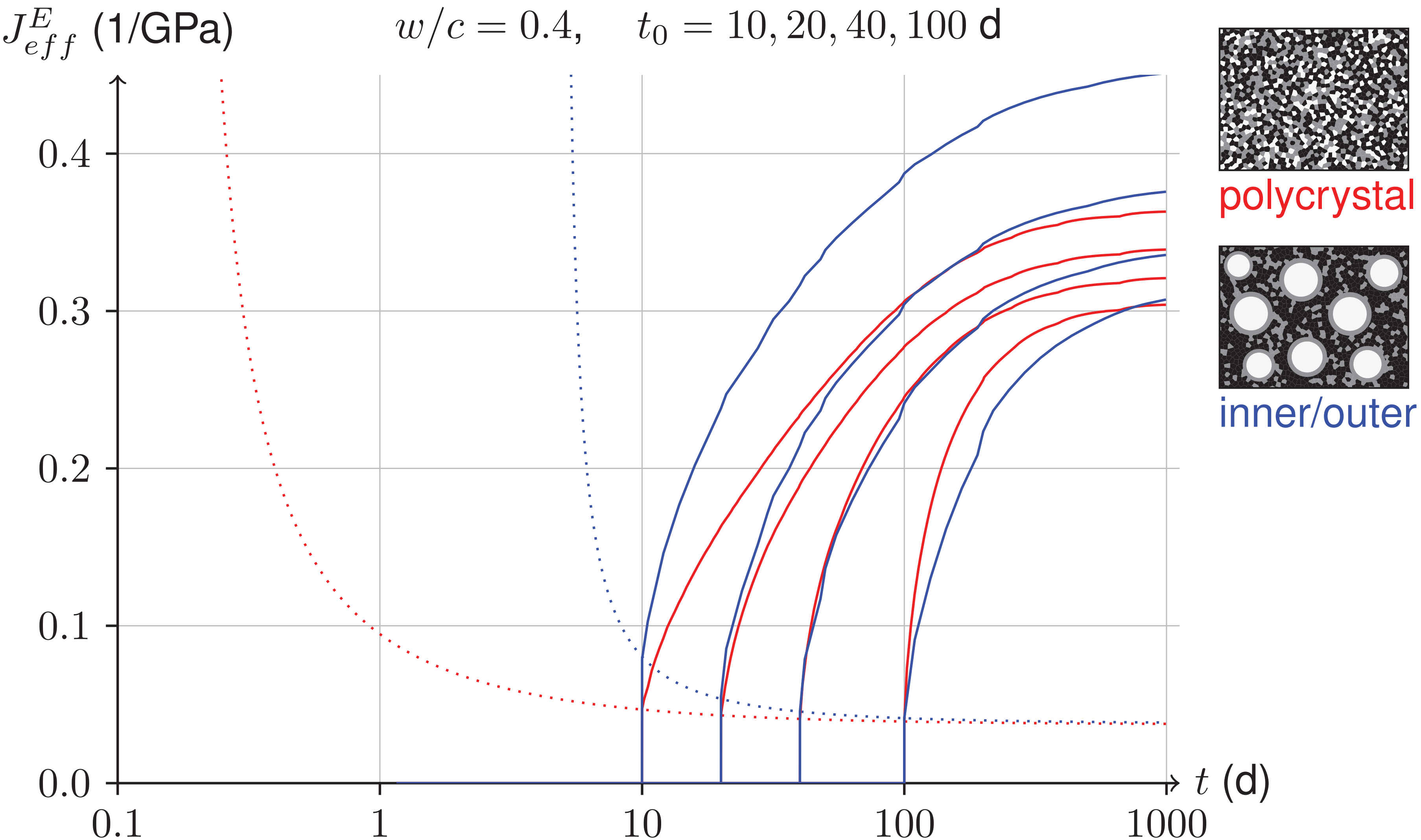



polycrystal

Effective uniaxial creep of cement paste



Conclusion

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- to challenge simplified morphological models
- a bridge between the scale of physical nano- or micro-mechanisms and the scale of structural engineering

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- quick and efficient computation, semi-analytical
- estimates and tendencies
- better understanding of the material behaviour

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Many behaviors can be investigated

- elasticity
- non ageing viscoelasticity
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- elasticity
- non ageing viscoelasticity
- ageing viscoelasticity
- elastic limit and strength
- post-peak behaviour
- plasticity
- transport (diffusion, conductivity, permeability, . . .)

Conclusion on ageing

Ageing viscoelastic homogenization, now made easy...

- classic homogenization schemes: dilute, MT, SCS
- spherical particles [J. Sanahuja, IJSS, 2013]
- N-layered spherical particles [to be published]
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… allows to un-freeze microstructure (phase transformations)
… and already (widely) adopted

- @ ENPC, an extension to elongated particles [F. Lavergne et al., submitted to IJSS, 2015]
- @ CEA, application to cementitious materials at early age [T. Honorio et al., Concreep, 2015]
- @ Cerema, application of the semi-analytical approach to a pre-stressed structure [J.F. Barthélémy et al., Concreep, 2015]
- @ Univ. Lorraine, application to rocks (starting collaboration with A. Giraud)

Prospects

Influence of hydration on ageing creep
can now be properly investigated

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- microprestress
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Experimental comparison on Vercors concrete

$\Rightarrow$ S. Huang PhD thesis (starting nov. 2015)

TU 1404
COST ACTION

Back to the list of presentations

TU1404 COST ACTION

THE LARGE IN-SITU EXPERIMENTAL CAMPAIGNS: CIVAUX AND CEOS.FR

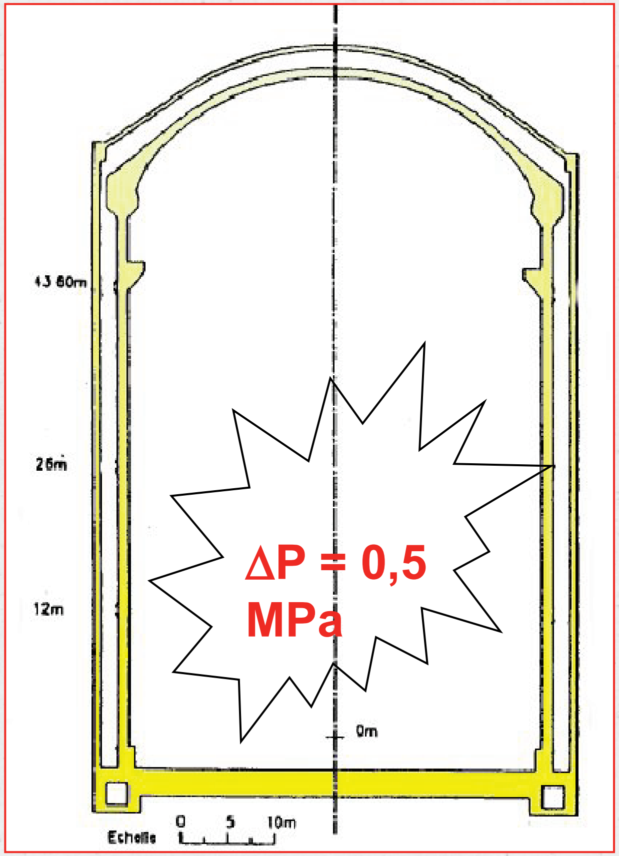
Jean Michel Torrenti - IFSTTAR, France

on behalf of CEOS.fr project

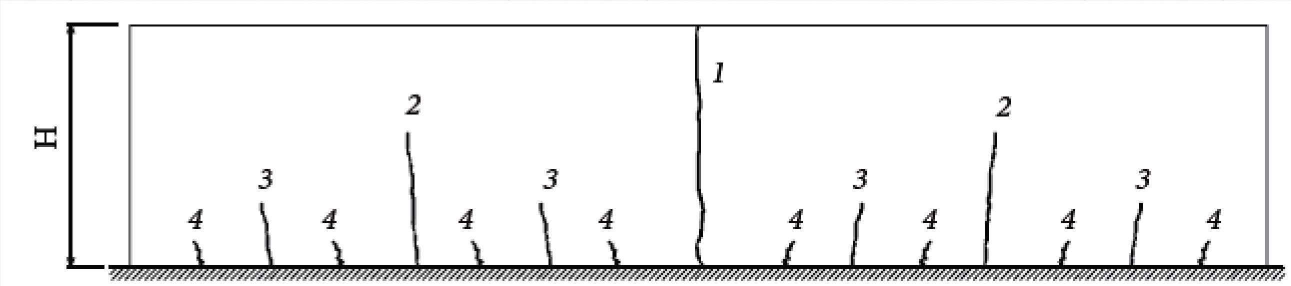
IFSTTAR

CONTEXT

Civaux nuclear power plant



Construction using successive layers

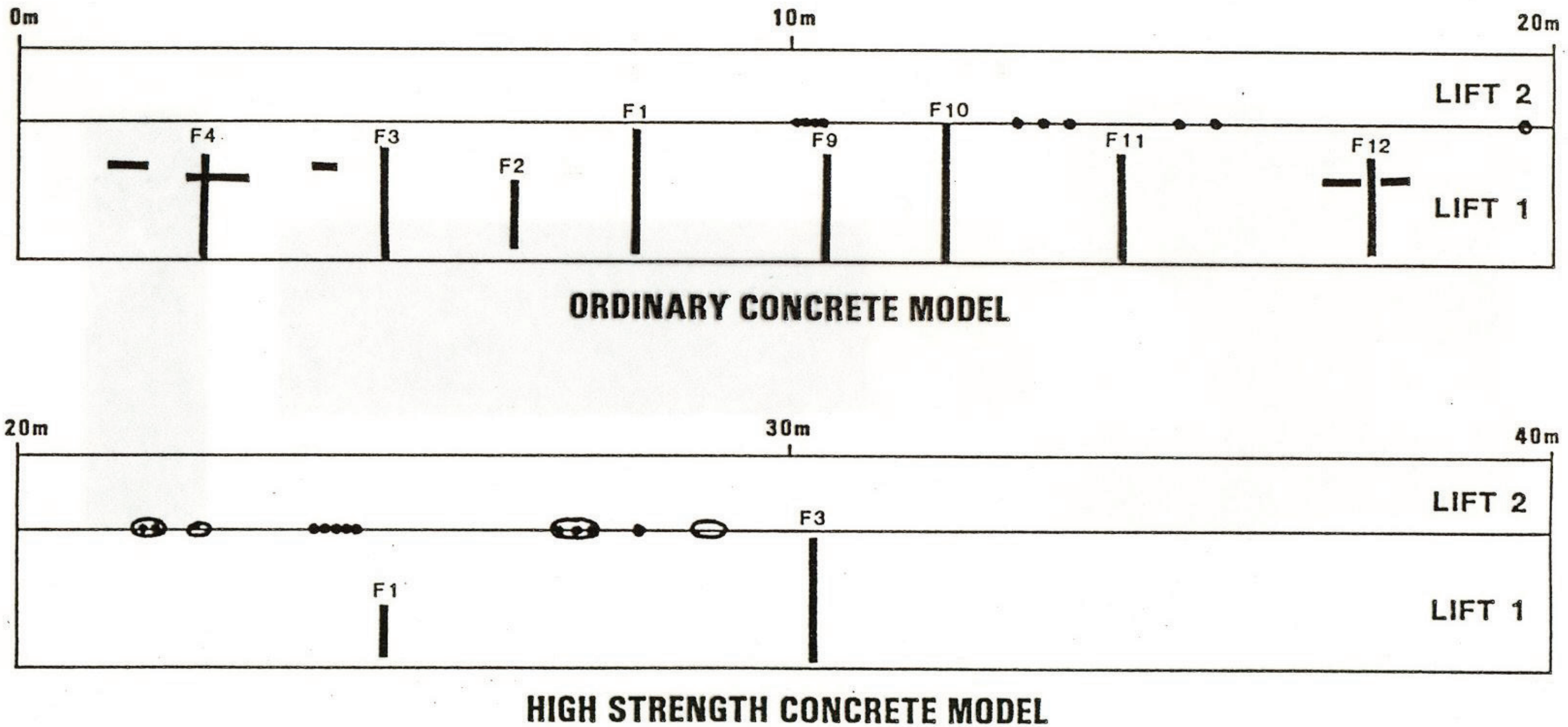


CIVAUX benchmark

- 2 NPP in Civaux with different mix-design of concrete:

Civaux 1	Civaux 2
agg = 1872 kg	agg = 1915 kg
CEMI	CEMII
c = 350 kg	c = 266 kg
	silica fume = 40 kg
w = 195 l (w/c=0.56)	w = 161 l (w/c=0.6 ; w/b=0.52)
sp = 1,2 l	sp = 9 l

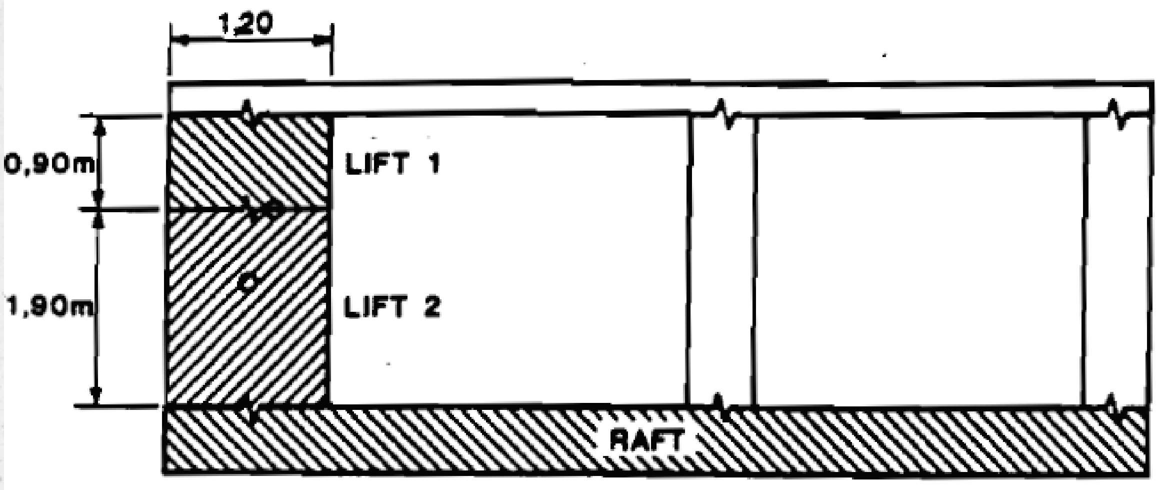
Crack pattern



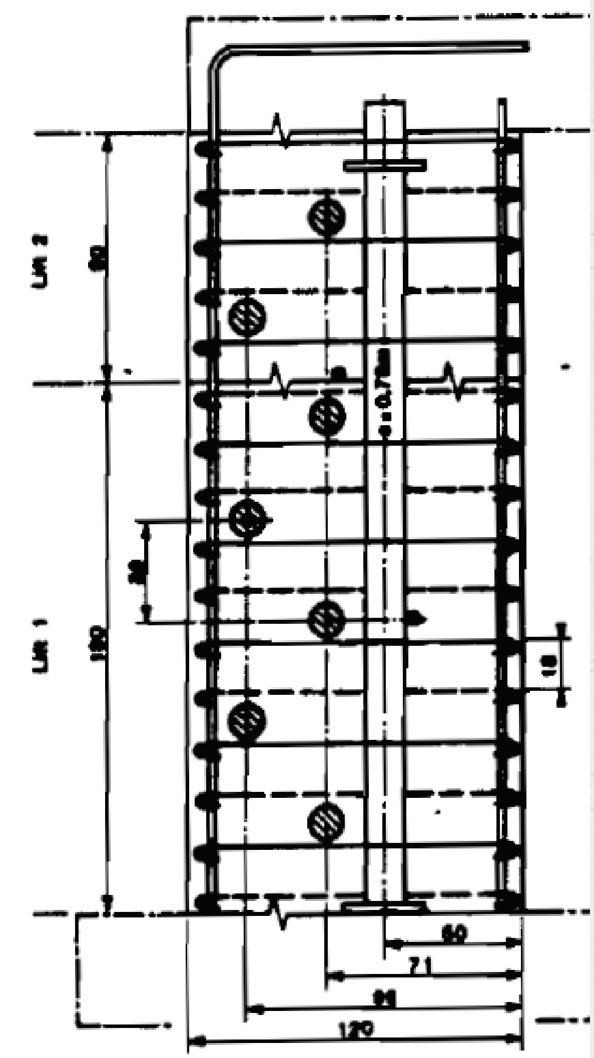
Correlated to the results of air leakage tests

Benchmark – available data

- Geometry



- Reinforcement



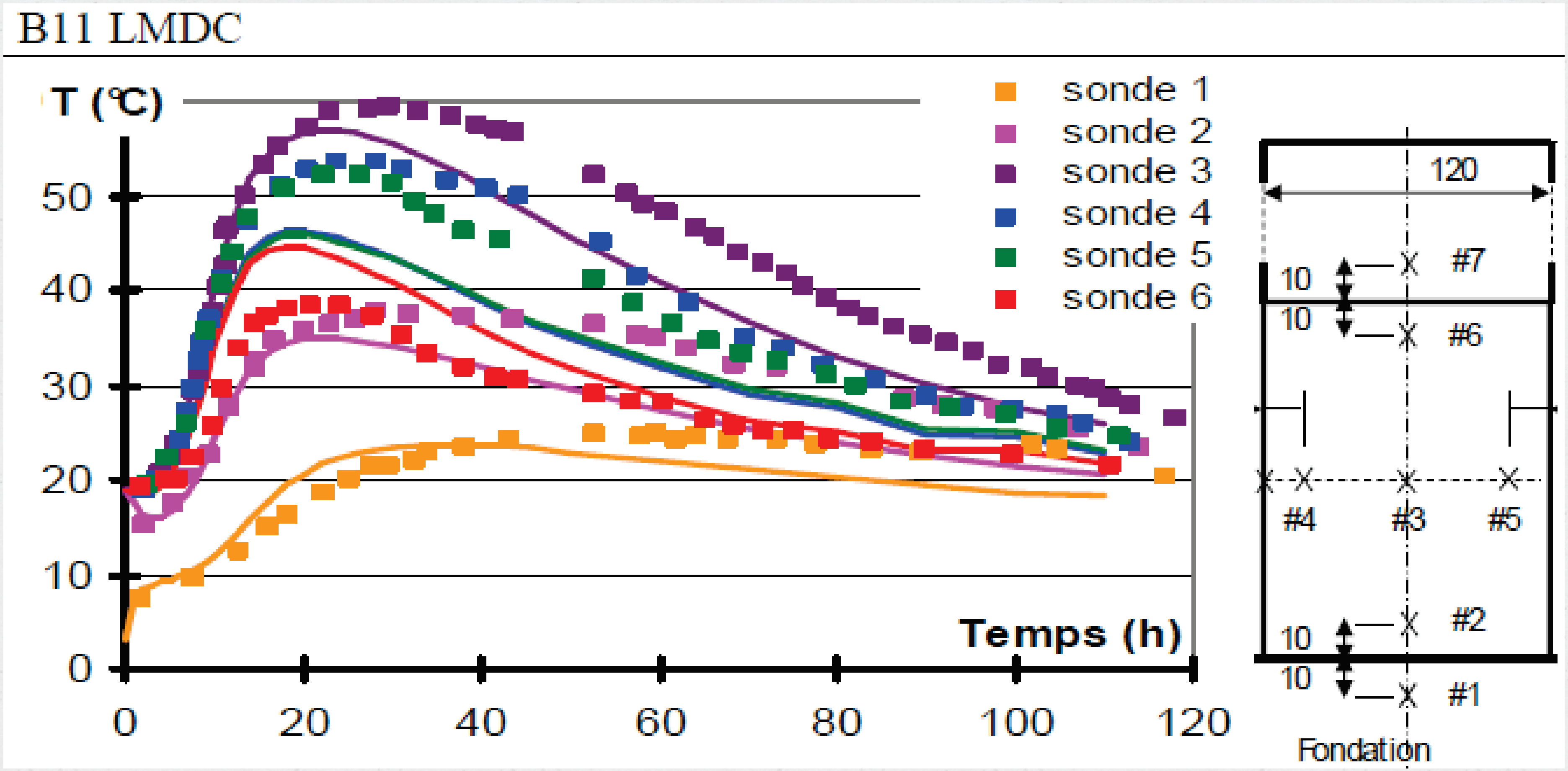
- External temperature evolution
- Initial temperature
- Nature of the formwork (wood 2cm)

- Heat of hydration of cement (Civaux 1) using EN 196-9 and cement + sf (Civaux 2)

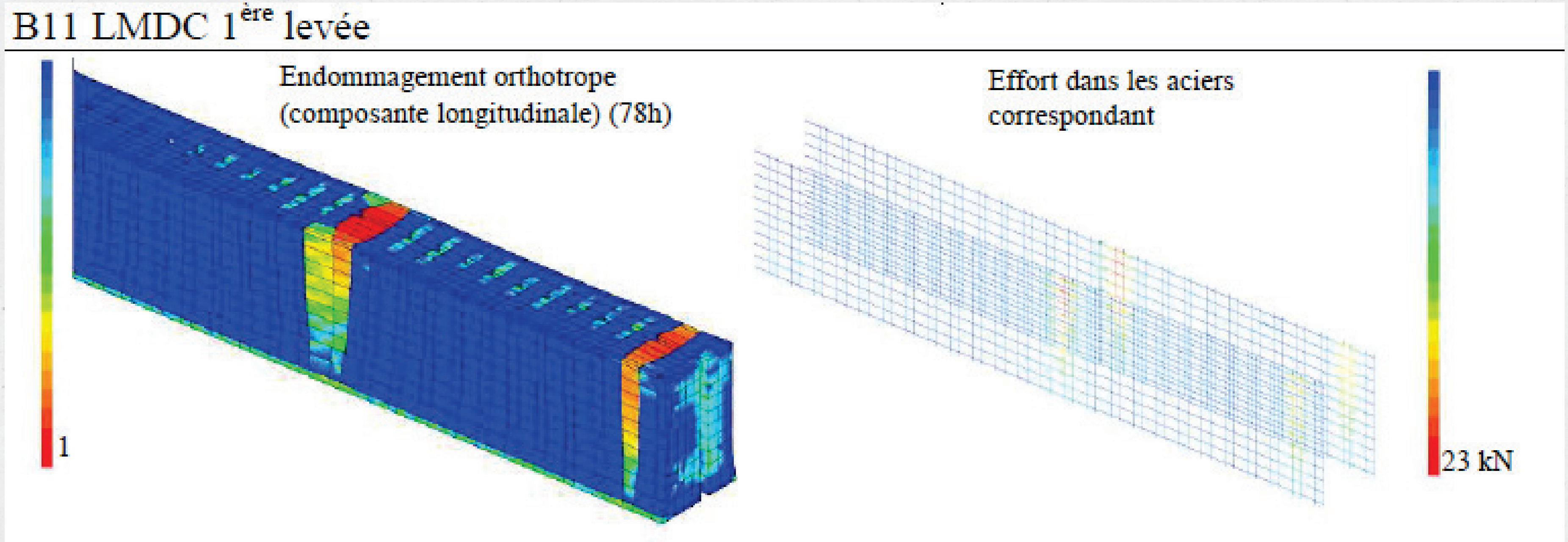
- Mechanical characteristics (but at 28 days and 1 year)

- Autogenous shrinkage, basic creep (loading at 28 days) – Granger PhD

Example of results / LMDC Toulouse



Damage



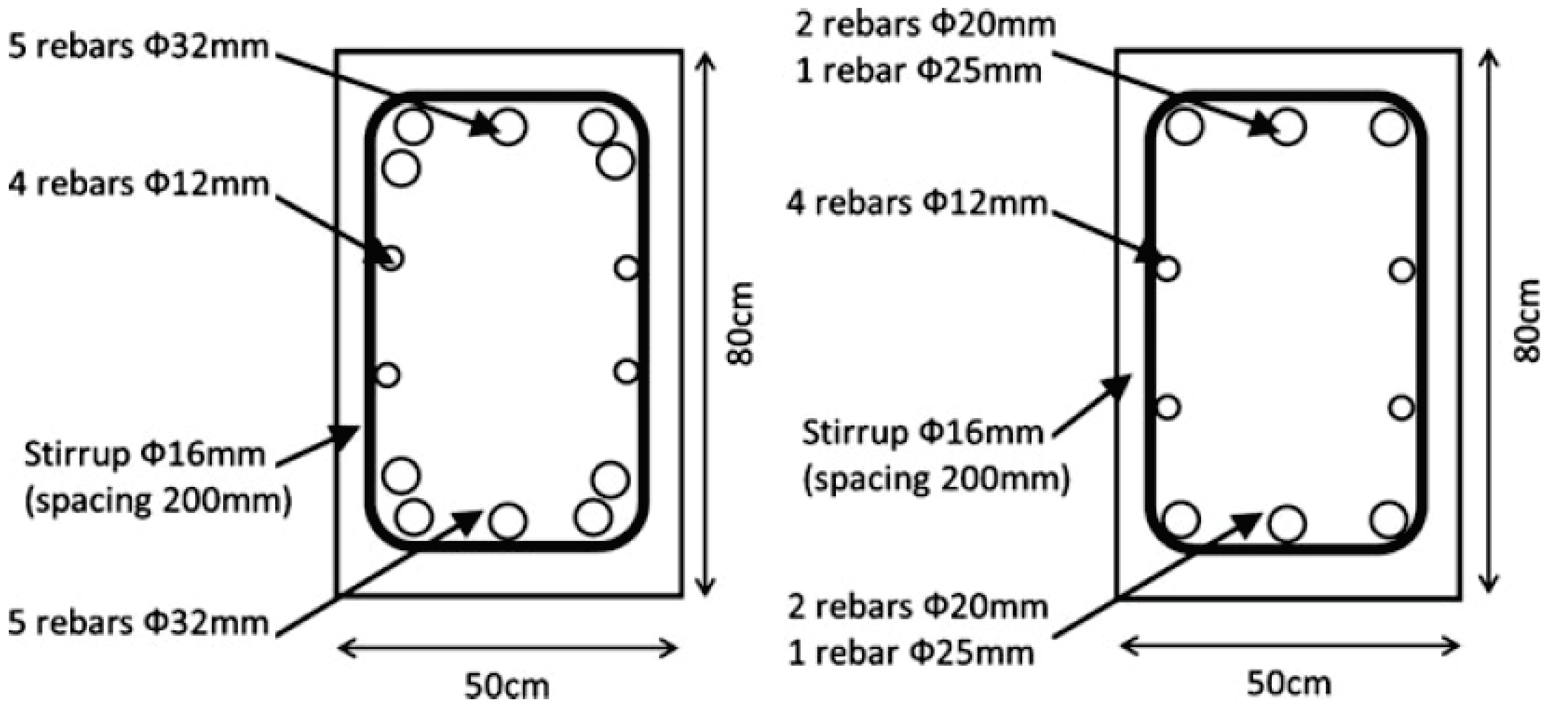
Need to use an orthotropic damage model in order to avoid spurious damage at the interface between the wall and the foundation.

(See also Benboudjema & Torrenti, NED, 2008)

CEOS.fr restrained shrinkage tests

- See Buffo-Lacarrière et al., EJECE, 2015
  http://dx.doi.org/10.1080/19648189.2015.1072587
- See https://cheops.necs.fr/ all results available !

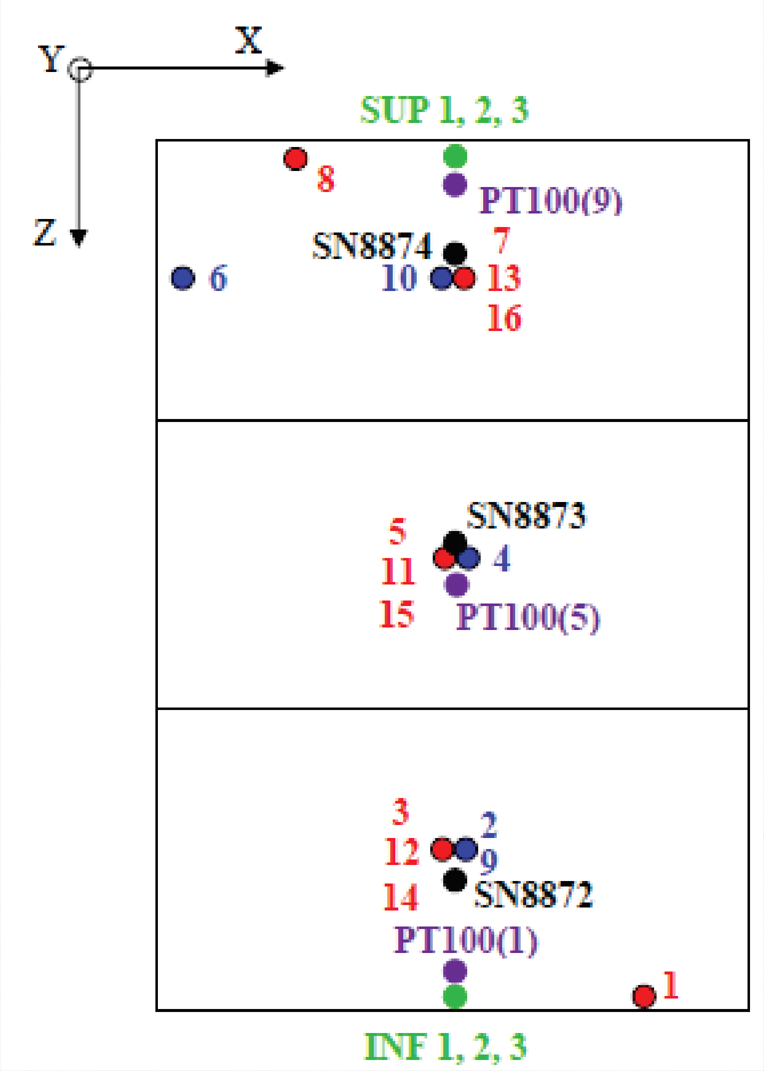
	RG8	RG9	RG10
% of longitudinal reinforcement	2%	.56%	2%
Cover	30 mm (50 mm for longitudinal rebars)	30 mm (50 mm for longitudinal rebars)	50 mm (70 mm for longitudinal rebars)

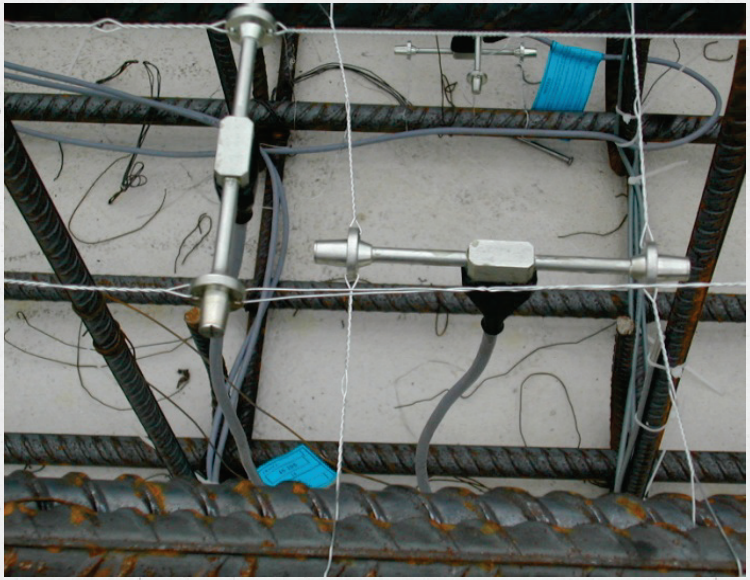


Instrumentation

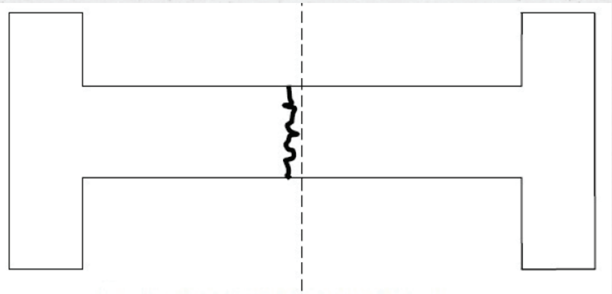
- 9 internal temperature probes (Pt 100 Ω type sensors)
- 16 vibrating wire extensometers (VWE) for local internal deformation measurement + 6 to measure the forces in the struts
- 3 internal long-base optical-fibre displacement sensors (Michelson type) (except for RG10 test)
- 6 electrical strain gauges (resistance type) placed on reinforcement bars (except for RG10 test).

Need of a thorough discussion with metrologists, in order to be sure of what is exactly measured and when!





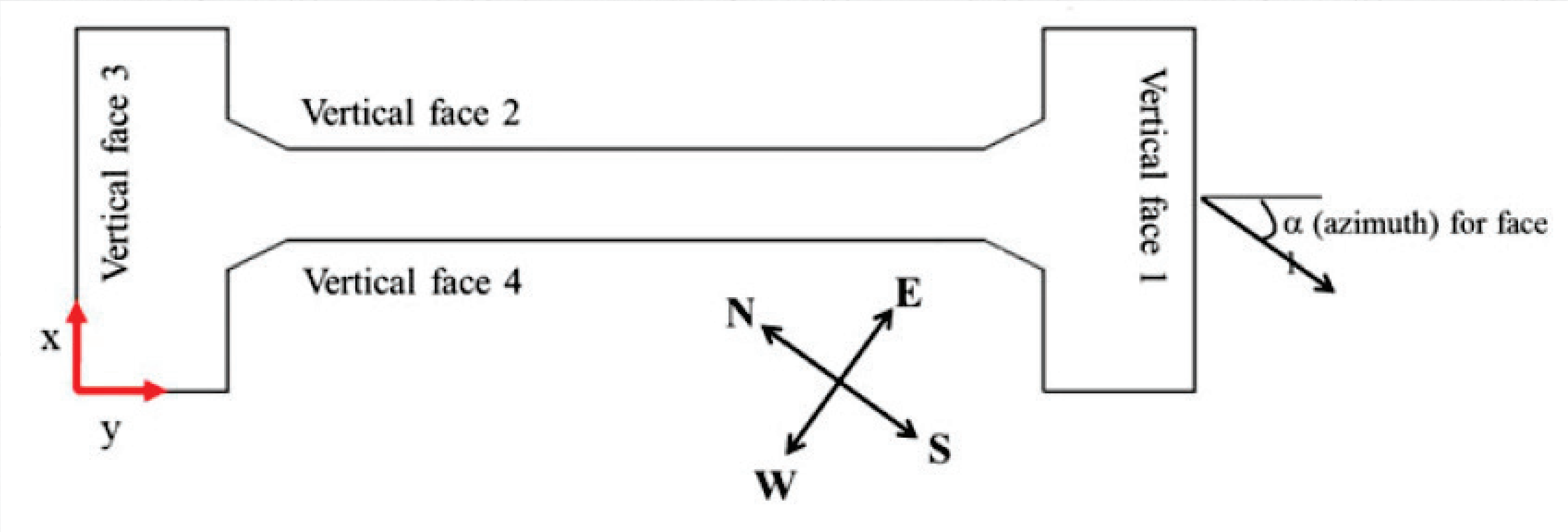
Influence of the presence of sensors on the behavior ???



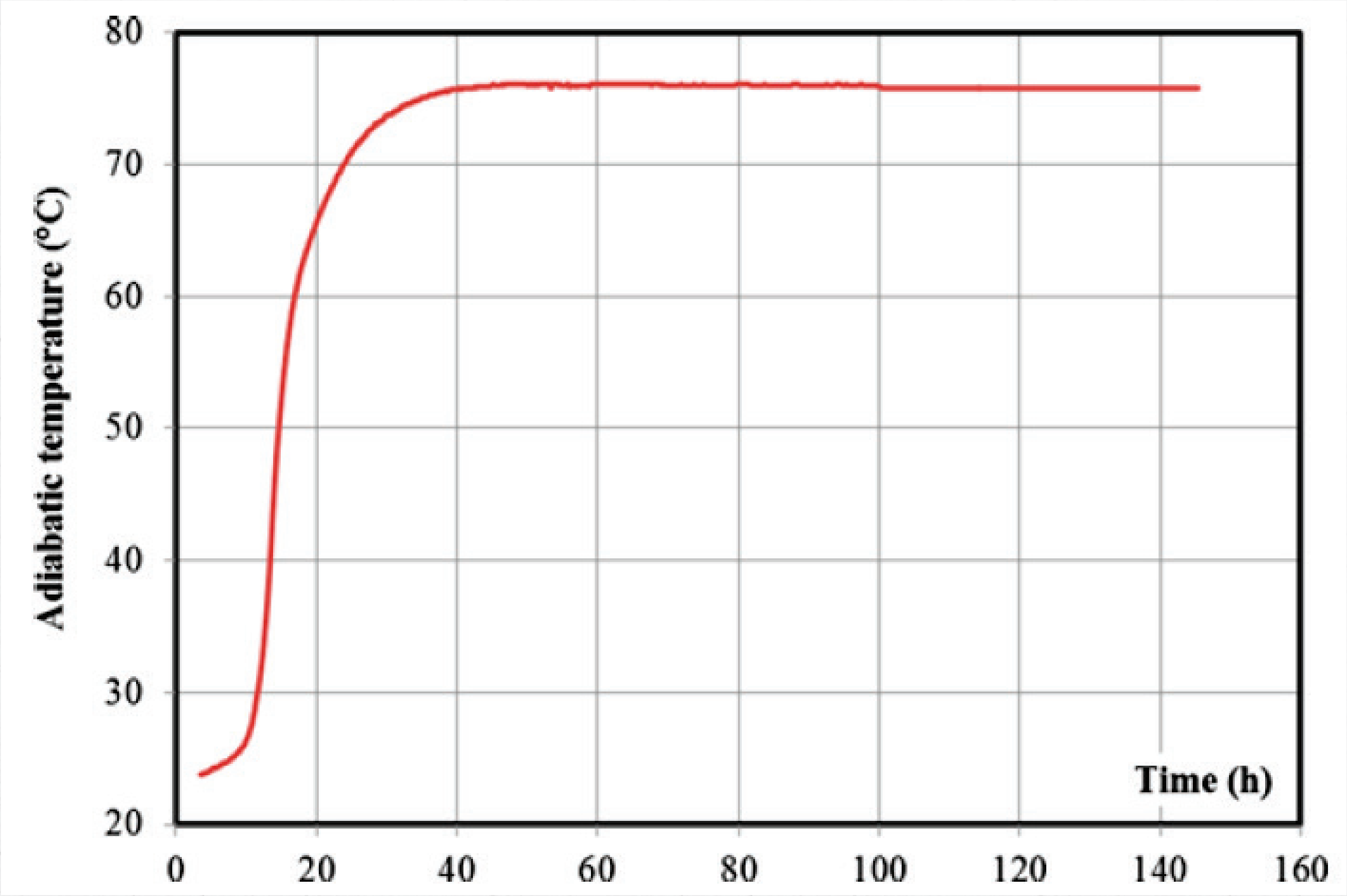
1st crack at 9h 40(UTC) 10/04/2010 - 75h after casting

Boundary conditions

- Influence of neighbourhood of the specimens and eventual shadow effect
- Nature of the formwork and insulation, age of concrete when formwork removal

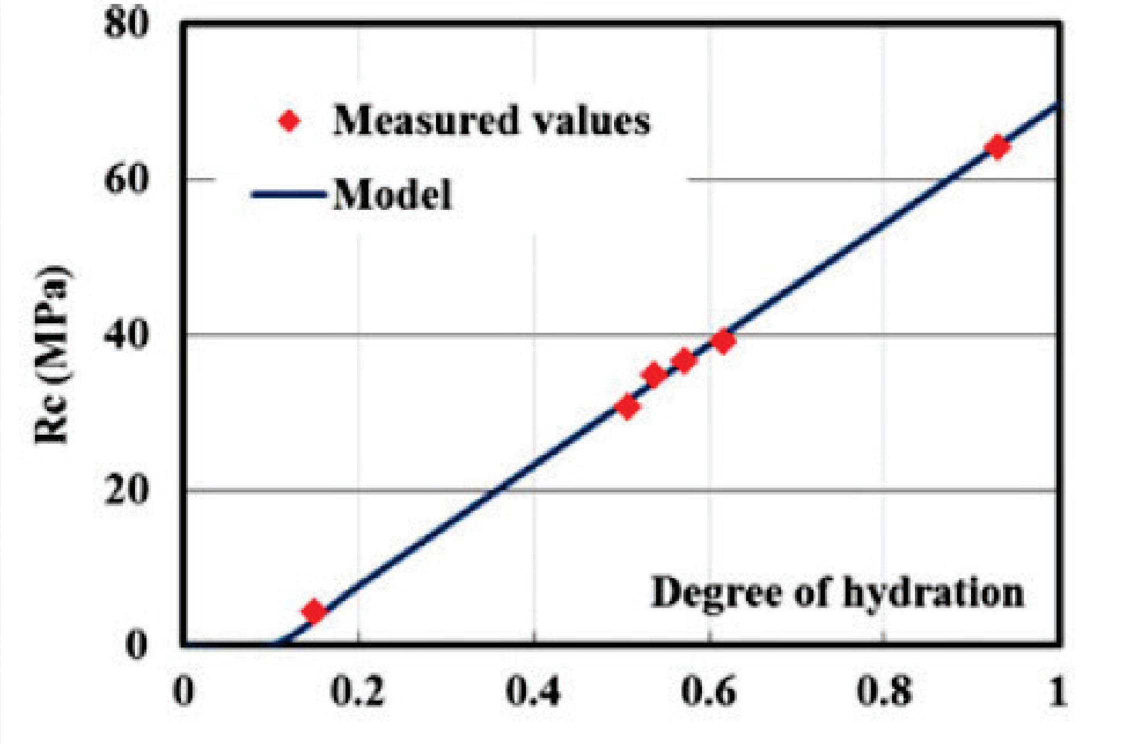


Adiabatic temperature rise (and it is really adiabatic)

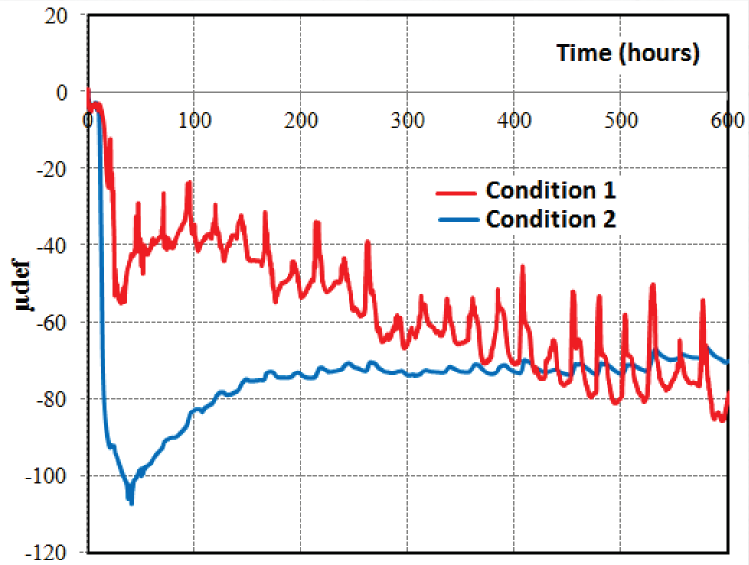


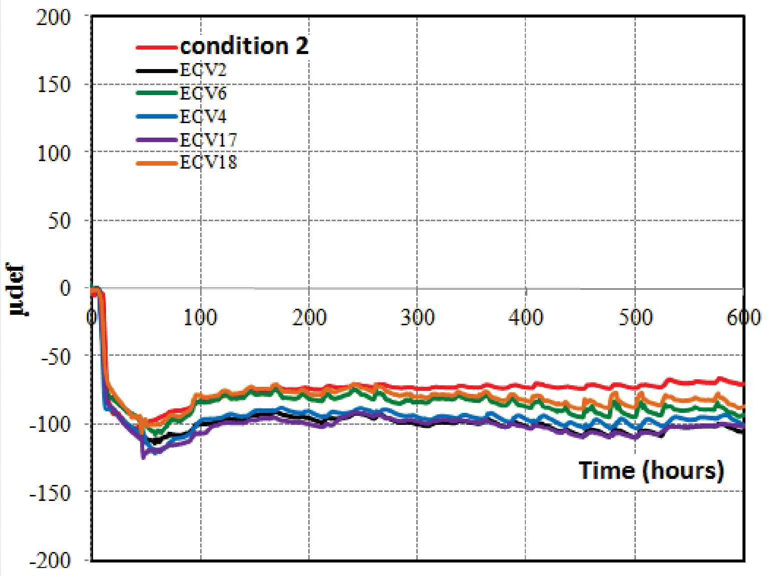
Mechanical characteristics at early age

- E, Fc, Ft, Gf measured with the degree of hydration
- Autogenous shrinkage, basic creep (loading at 7 days)



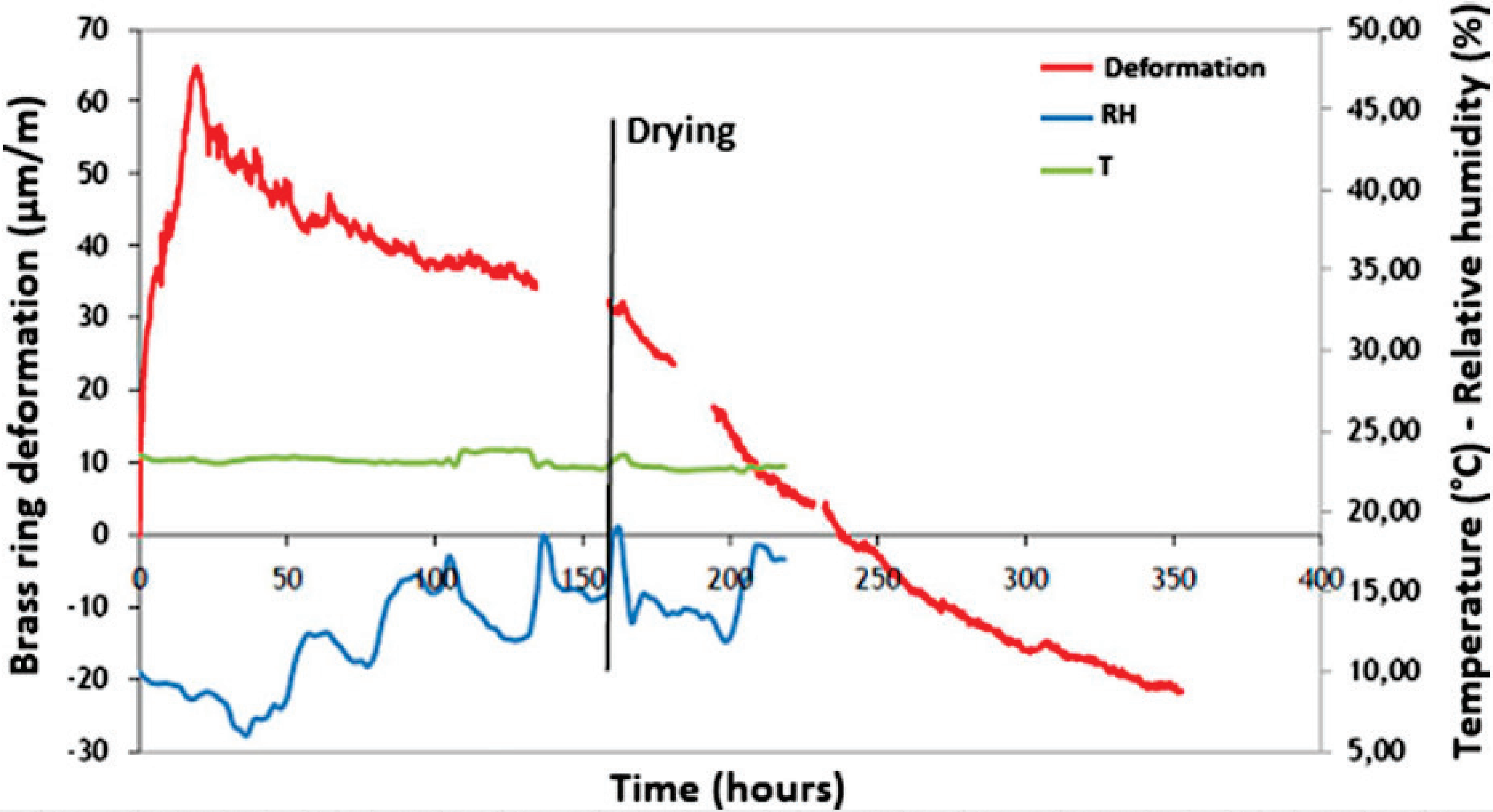
Specific test 1: comparison between free deformations in quasi-adiabatic conditions or local temperatures



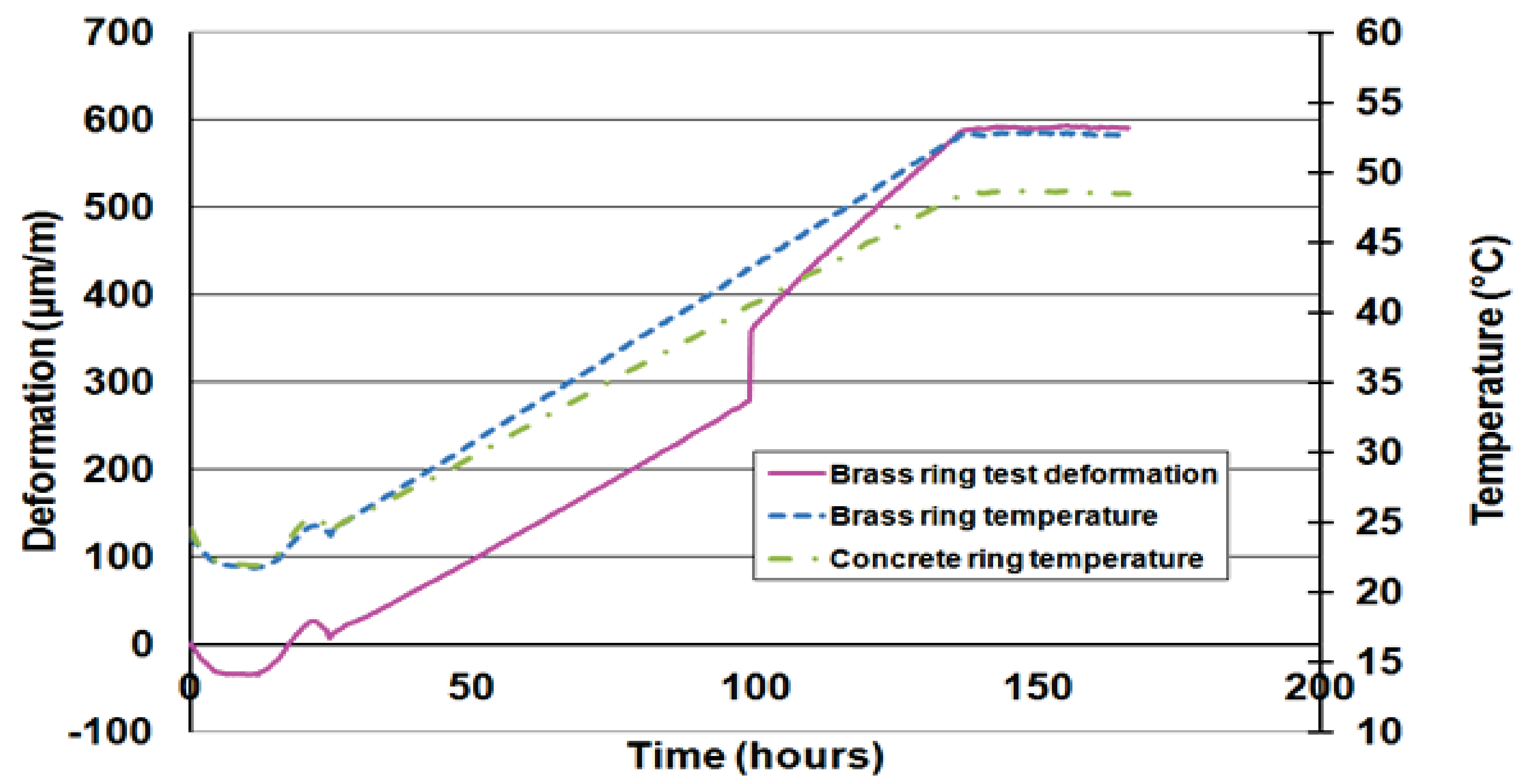


Comparison with transverse deformations measured with VWE
RG10 beam

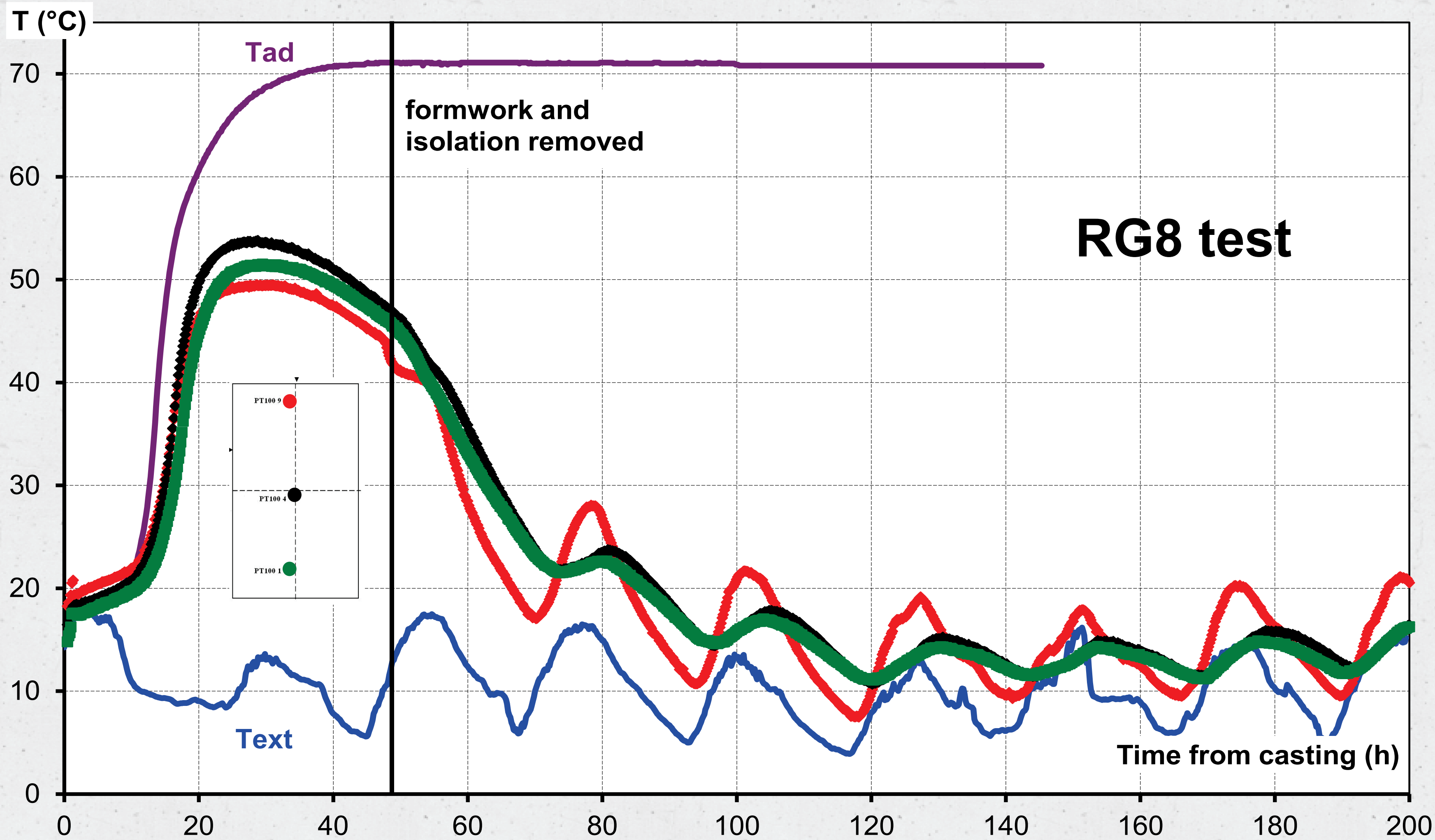
Specific test 2: ring test



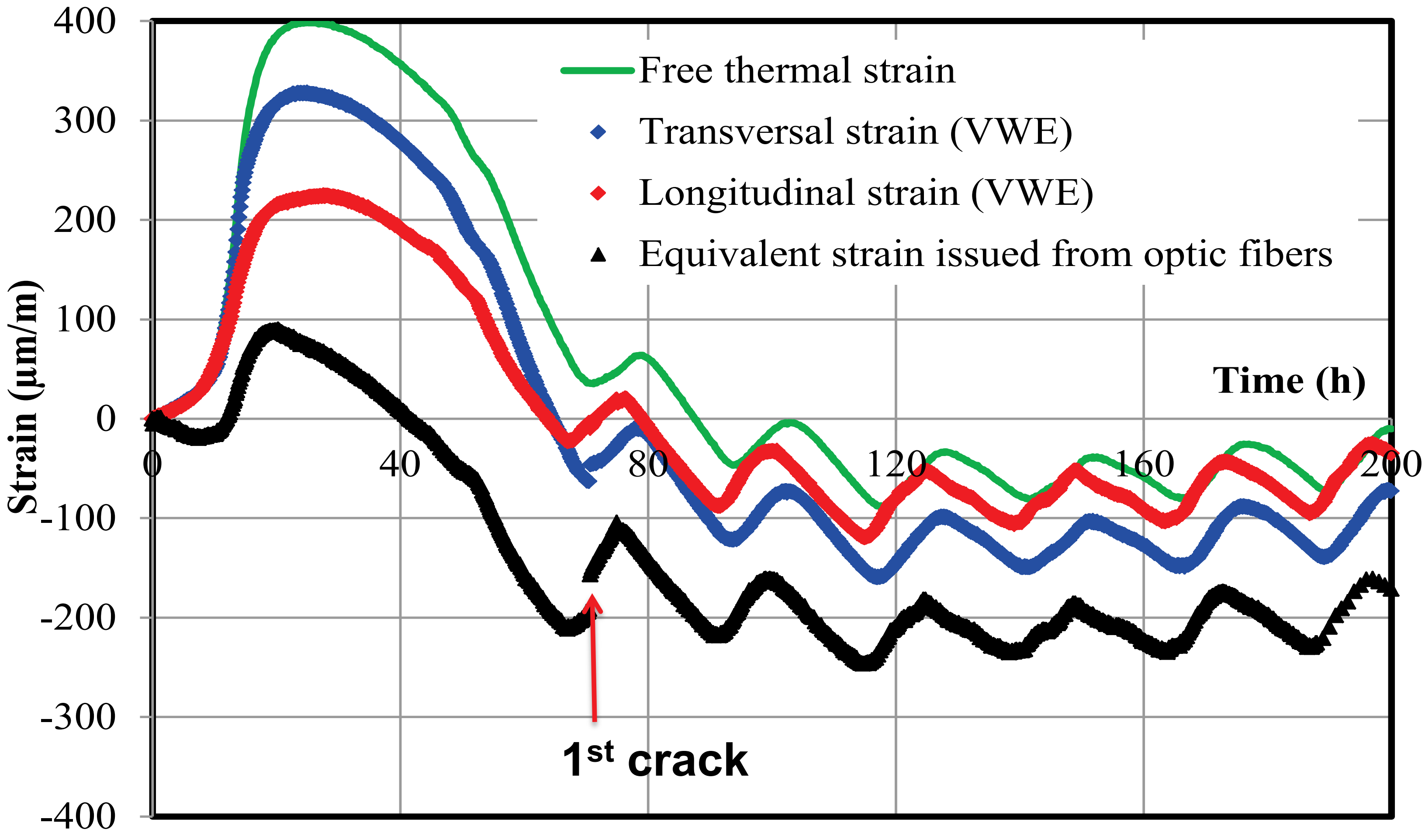
Specific test 3: active ring test (Briffaut et al., 2011)

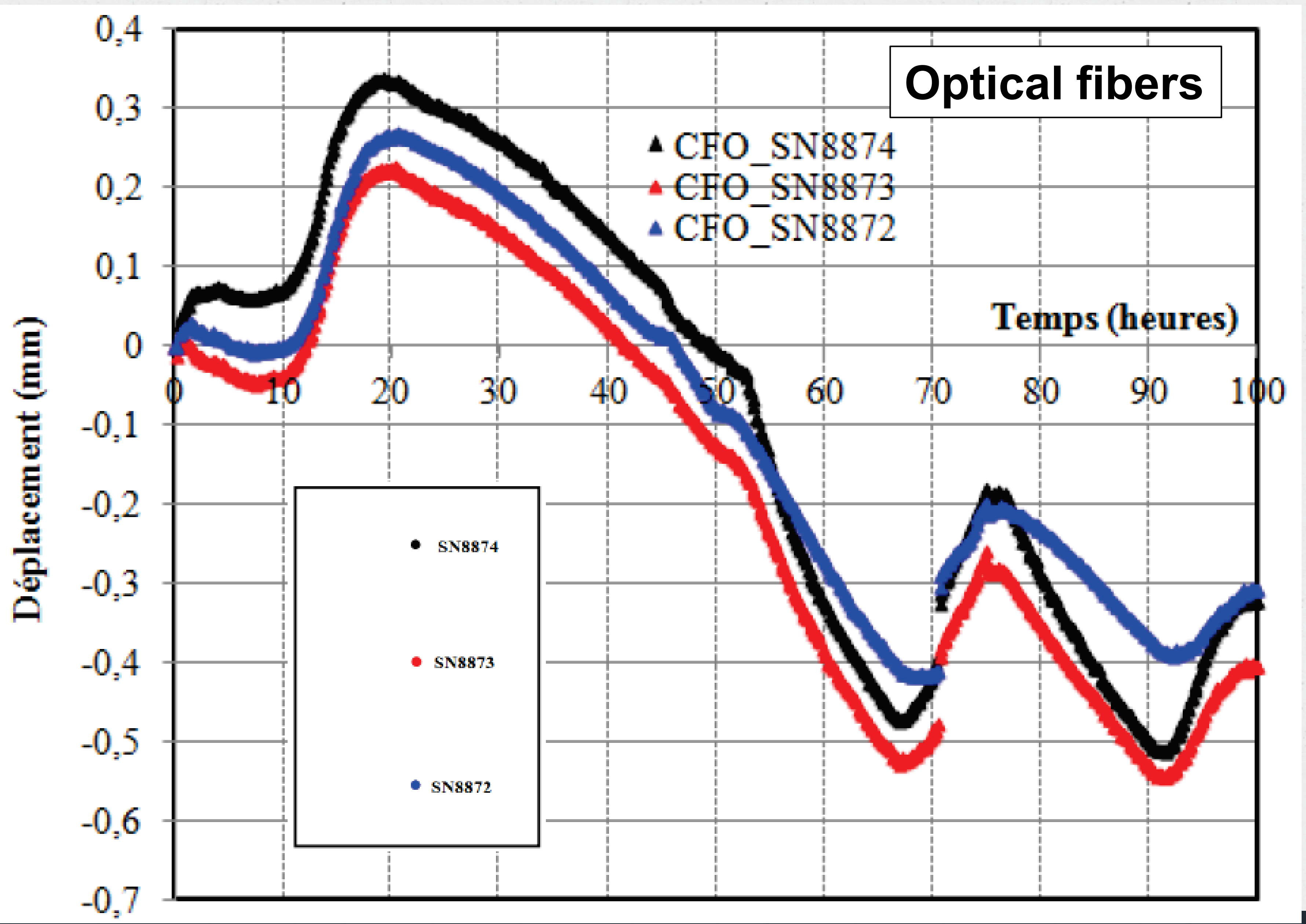


Results: temperature evolution

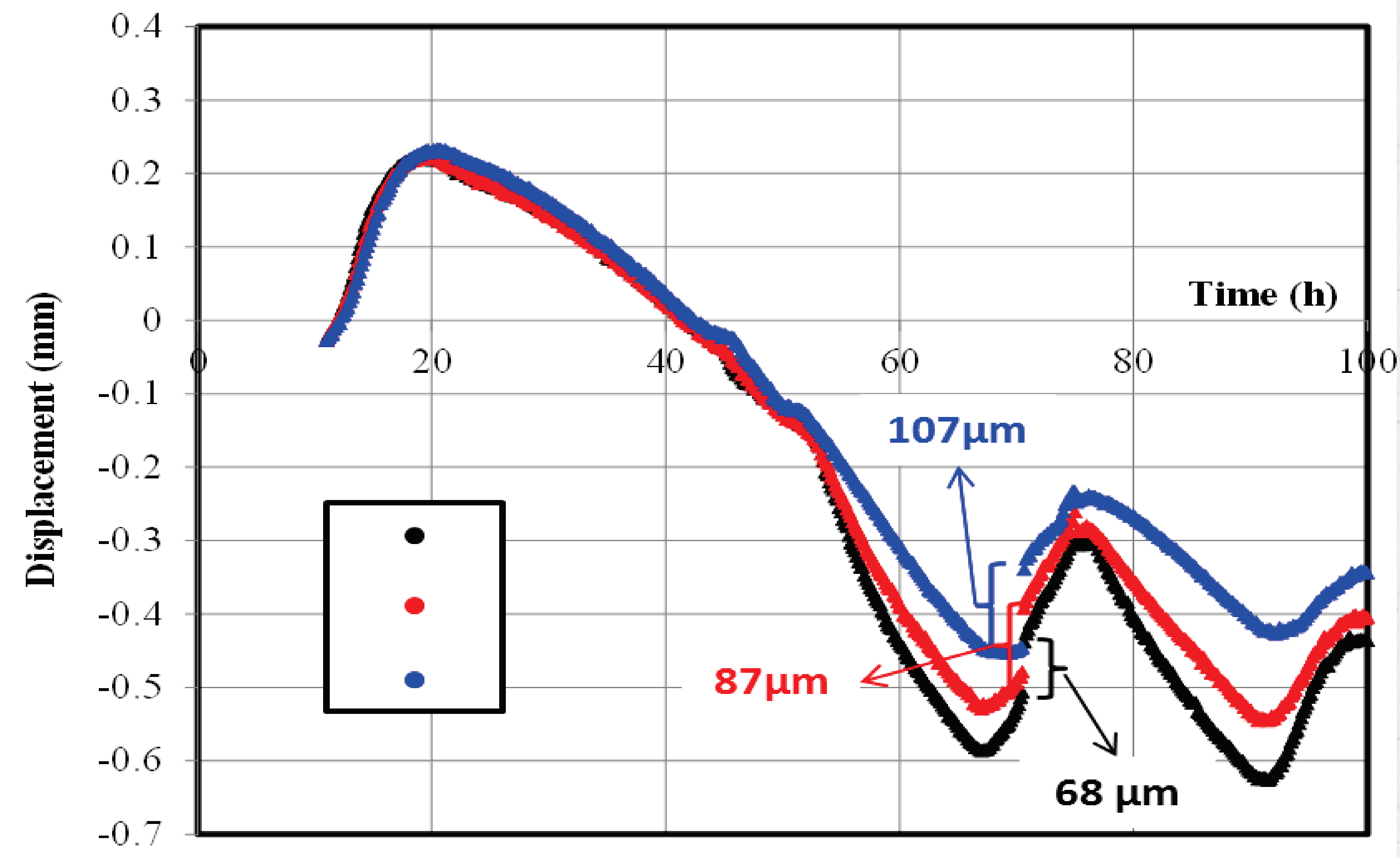


Results: strains

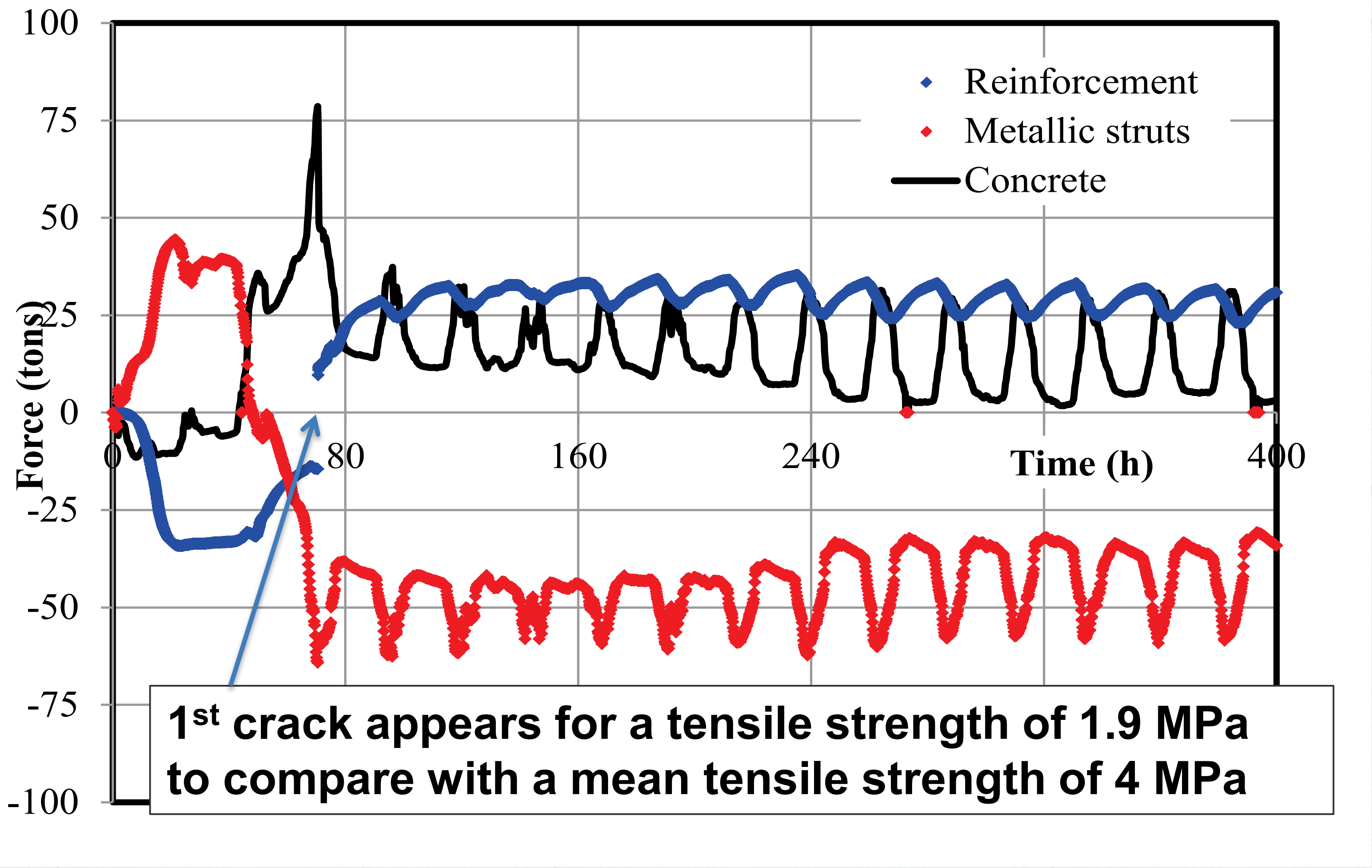



Optical fibers
CFO_SN8874
CFO_SN8873
CFO_SN8872
Temps (heures)
Déplacement (mm)
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
0
10
20
30
40
50
60
70
80
90
100
SN8874
SN8873
SN8872

Results: strains with optical fibers



ANALYSIS: AN EXAMPLE



1st crack appears for a tensile strength of 1.9 MPa to compare with a mean tensile strength of 4 MPa

CONCLUSIONS

- These two tests are available for benchmarking
- Civaux test: certainly not an extended example (as defined yesterday) but a possible case study, already used (by French teams)
- CEOS RG tests: more extended, all data freely available, already used (Concrack2 benchmark)

“A theory is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it” — Albert Einstein

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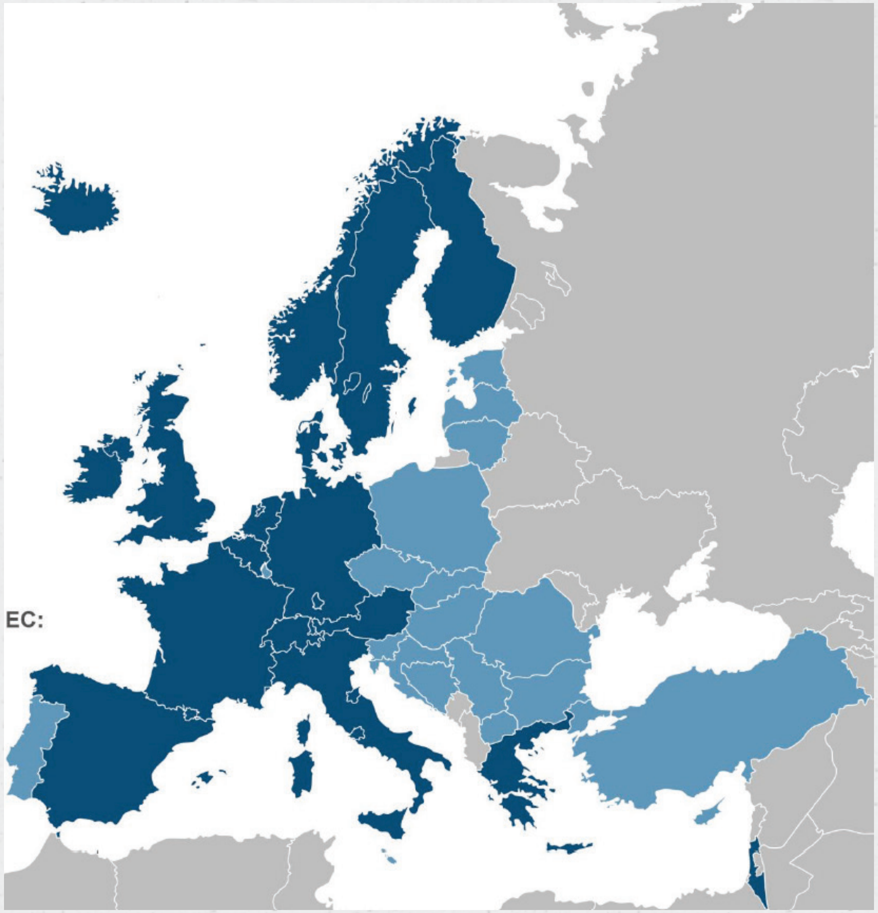
Closing Session

2nd COST TU1404 Action Meeting – Vienna, September 20, 2015

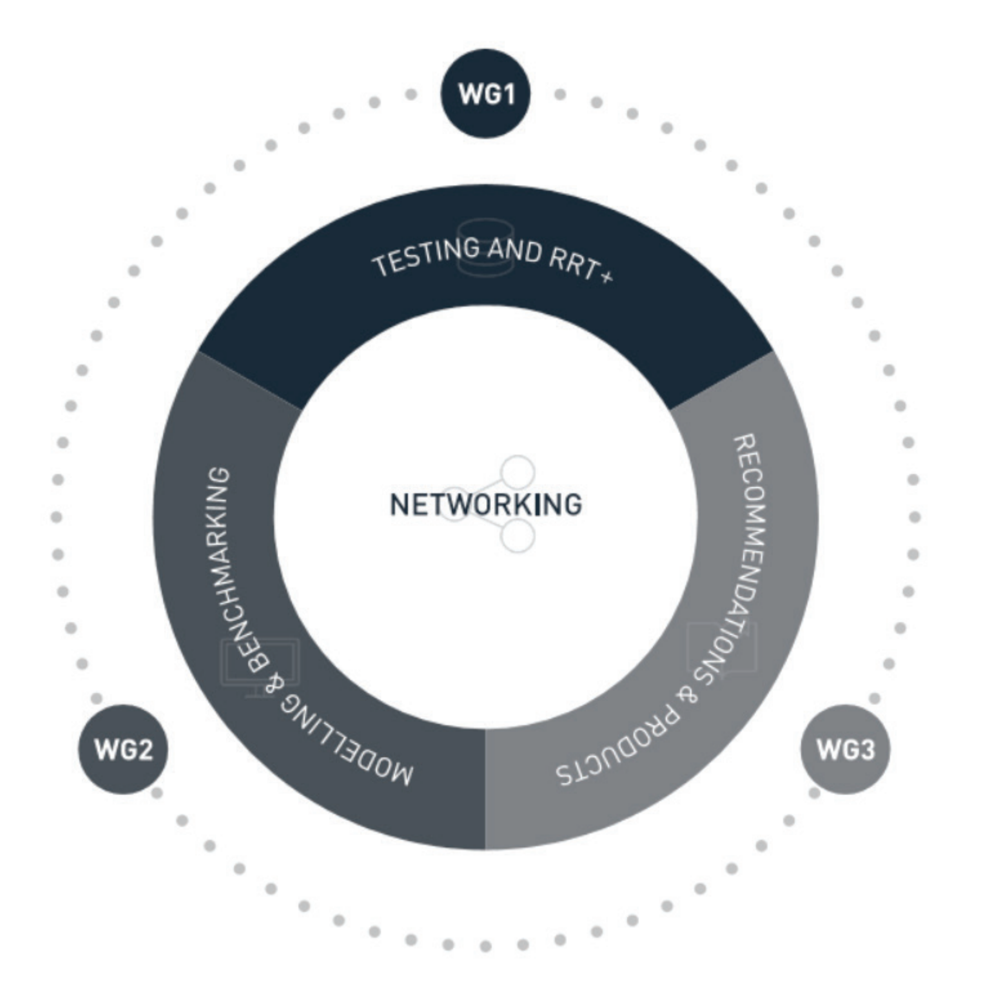
Members of COST TU1404



- 29 COST Countries
- 1 NNC – Ukraine (Algeria also coming in)
- 1 IPC – Australia (Japan also coming in)

- 226 individual members
- 42% are Early Stage Researchers
- Gender balance: 75% Male; 25% Female

What a year! :)



GENERAL LEADERSHIP

—

Chair: Miguel Azehna, University of Minho, Portugal
Vice-Chair: Stéphanie Staquet, ULB Bruxelles, Belgium
General Secretary: Dirk Schlicke, Graz University Of Technology, Austria

WG1
TESTING OF CEMENT-BASED MATERIALS AND RRT+

—

Grega Tritnk, Igmat, Slovenia
Marijana Serdar, University of Zagreb, Croatia
Sreejith Nanukuttan, Queen's University Belfast, United Kingdom

WG2
MODELLING AND BENCHMARKING

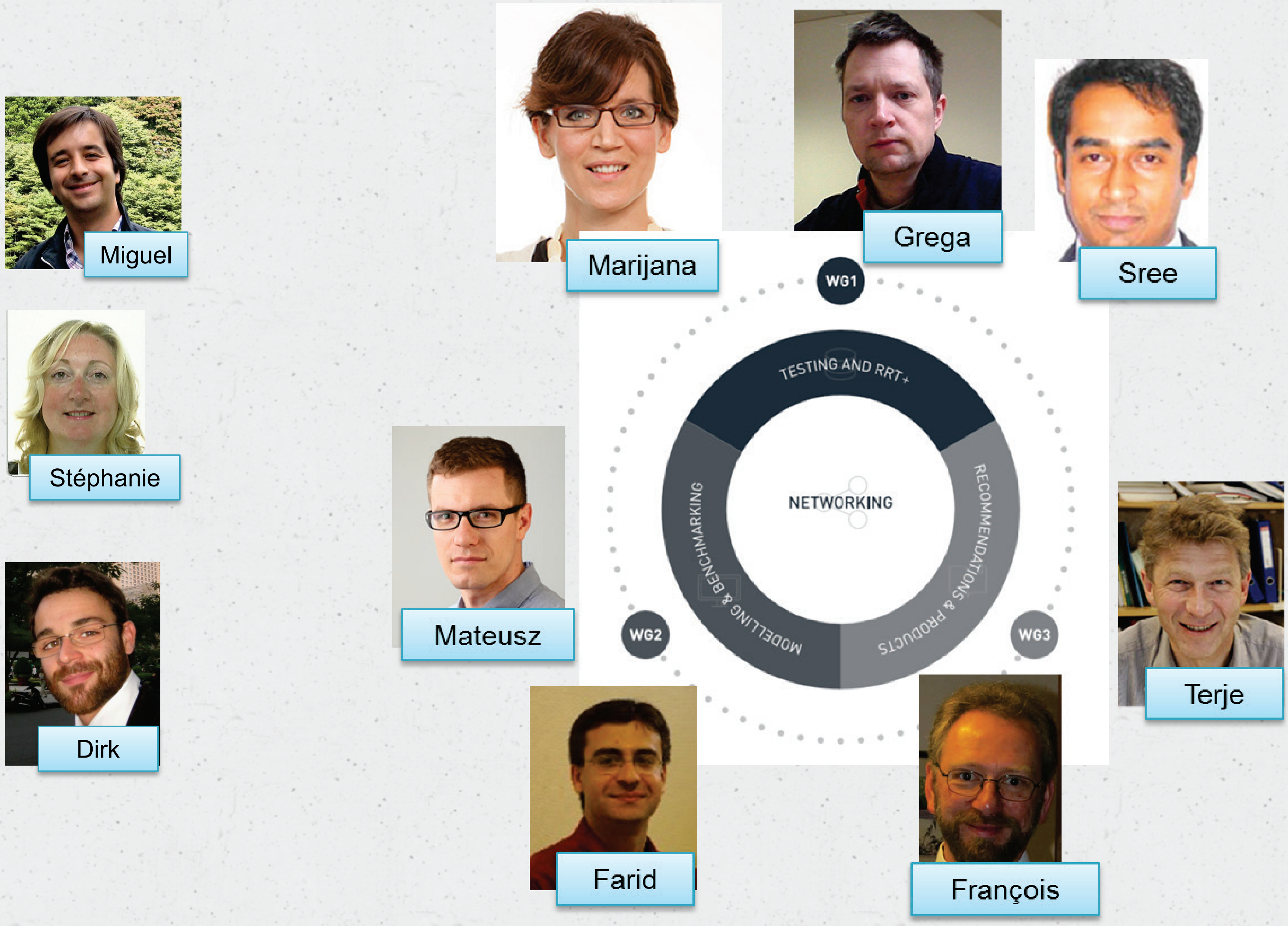
—

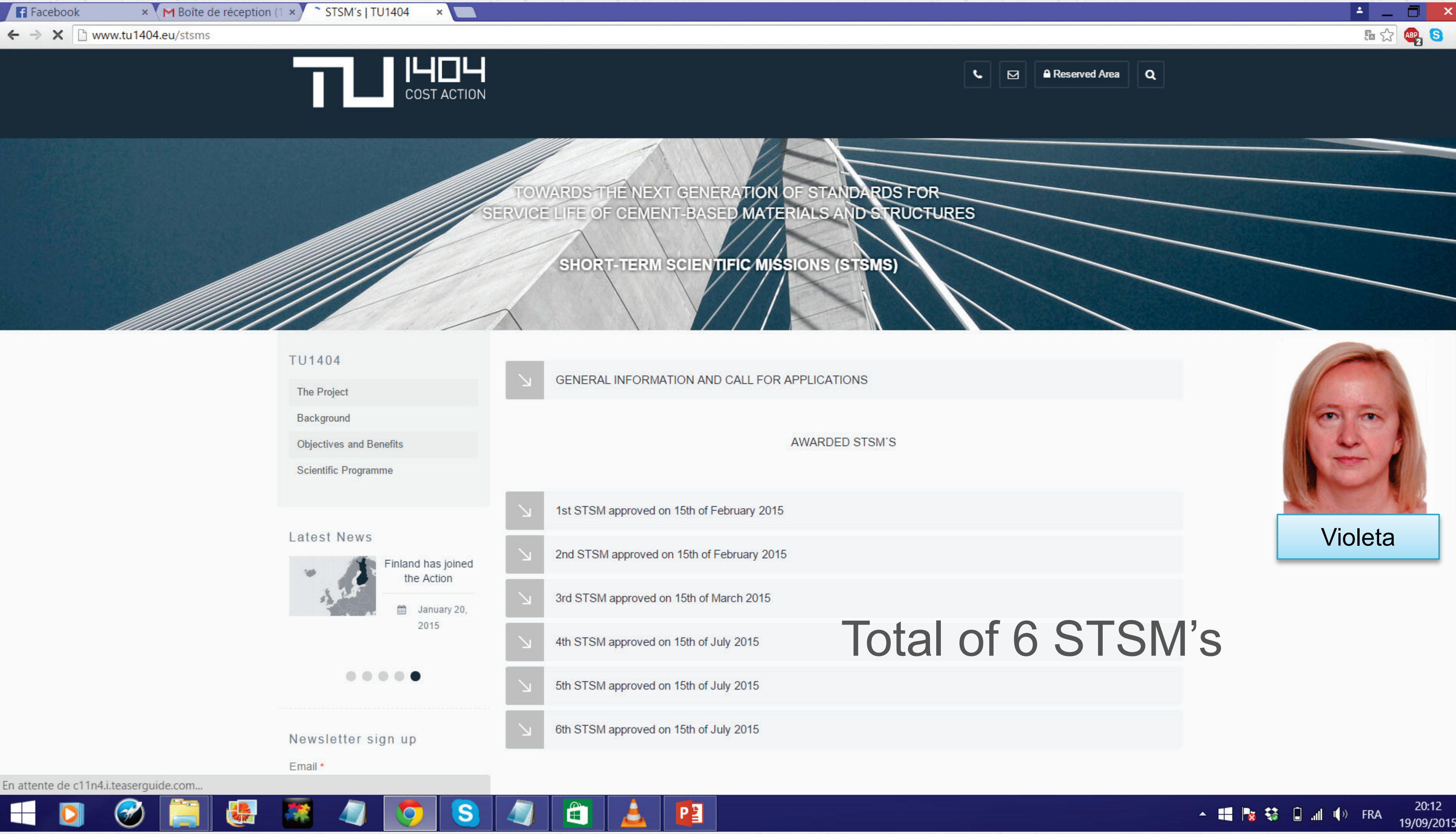
Mateusz Wyrzykowski, Empa Switzerland and Lodz University of Technology, Poland
Farid Benboudjema, ENS Cachan, France

WG3
RECOMMENDATIONS AND PRODUCTS

—

François Toutlemonde, Ifsttar, France
Terje Kanstad, NTNU Trondheim, Norway

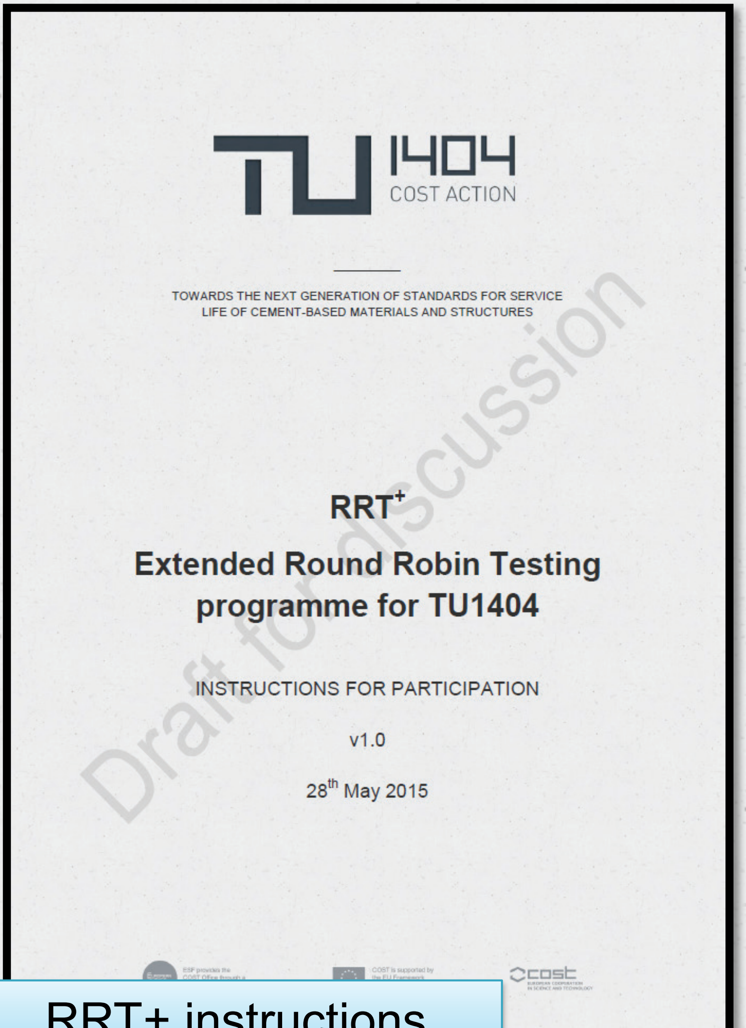

Miguel
Marijana
Grega
Sree
Stéphanie
Mateusz
Terje
Dirk
Farid
François
WG1
WG2
WG3
TESTING AND RRT+
NETWORKING
MODELLING & BENCHMARKING
RECOMMENDATIONS & PRODUCTS



Total of 6 STSM's

Violeta

What a year, ready for the initial phase of RRT+ !


TU 1404
COST ACTION

TOWARDS THE NEXT GENERATION OF STANDARDS FOR SERVICE LIFE OF CEMENT-BASED MATERIALS AND STRUCTURES

RRT+

Extended Round Robin Testing programme for TU1404

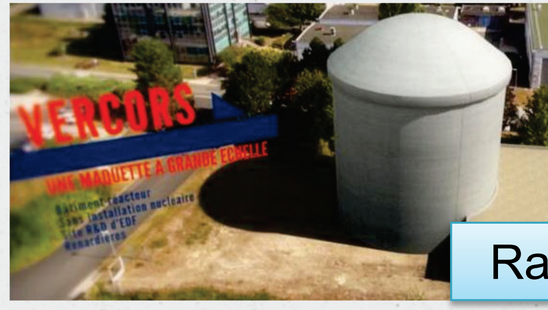
INSTRUCTIONS FOR PARTICIPATION

v1.0

28th May 2015

Draft for discussion

RRT+ instructions



EDF

Raw materials supply

BUILDING TRUST Sika

GSM Italcementi Group

SMN Société des Matériaux de Nogent

Materials on the way!

CEVA

WG2 Modelling of CBM and the Behavior of Structures

- Vienna, Austria, September 2015

78 participants

- Organized by Mateusz Wyrzykowski, Bernhard Pichler, Farid Benboudjema and Dirk Schlicke

Group priorities		Part.	Leaders		
			Surname	**Name**	**Country**
GP2a	Microstructural modelling	31	Guang	Ye	The Netherlands
GP2b	Multiscale Modelling	43	Dunant	Cyrille	Switzerland
			Pichler	Bernhard	Austria
GP2c	Macroscopic modelling	43	Gawin	Dariusz	Poland
			Briffaut	Matthieu	France
GP2d	Probabilistic Modeling	26	Max	Hendriks	Norway
			Caspeele	Robby	Belgium
GP2e	Numerical Benchmarking	38	Buffo-Lacarrière	Laurie	France
			Knoppik-Wróbel	Agnieszka	Poland

What a year, WG2 : Modelling of CBM
81 participants
Numerical benchmarking, Stage 1 starting soon!

- **Stage I – simple examples**

  get to know and better integrate different modeling tools used by different participants; help in future implementation of new models

  Time frame: announced April 2015, finished by the end of 2015

Doctoral course

Technical University of Denmark

DANISH TECHNOLOGICAL INSTITUTE

Materials, Systems and Structures in Civil Engineering

MSSCE 2016

Service Life of Cement-based Materials and Structures

Conference segment | **Doctoral course**

Scope of doctoral course segment

Service life of cement-based materials is a topic of substantial importance since the maintenance of concrete structures every year necessitate massive investments in rehabilitation and repair. However, constantly ongoing research refines our theoretical knowledge about why deterioration takes place, models for prediction of deterioration are improved, and new measures to prevent deterioration processes appear and extend the service life of concrete structures. This course brings you up-to-date on this important area.The doctoral course segment will bring you up-to-date on this important area.

Course contents

The course will cover the most important topics in relation to service life of cement-based materials including:

- Fresh properties and setting
- Chemical & microstruct characterization
- Transport properties & boundary effects
- Mechanical properties
- Volume stability
- Fracture properties and cracking
- Multi-scale models
- Multi-physics macroscopic modelling
- Modelling assumptions
- Product developm for testing/monitoring
- Product development for software
- Reliability considerations
- Recommendations, pre-standard docum

Contact:

Ole Mejlhede Jensen
Send e-mail

Organizing committee:

Miguel Azenha
TBD
O.M. Jensen

15-19
August 2016

Further info:

Work load: 140 hours

Next COST ACTION conference

TU 1404 COST ACTION

DTU Technical University of Denmark

rilem

DANISH TECHNOLOGICAL INSTITUTE

Materials, Systems and Structures in Civil Engineering

MSSCE 2016

Service Life of Cement-based Materials and Structures

Conference segment | Doctoral course

The main objective of COST Action TU1404 is to bring together researchers and practitioners in the pursuit of knowledge integration for better understanding of the service life of cement based materials and structures. This conference segment is dedicated to the discussion and dissemination of relevant results of Action members, but also from any researcher or practitioner reporting work related to the Workgroups and Group Priorities of the Action.

WG1 - Testing of CBM

GP1a - Fresh properties and setting
GP1b - Chemical / microstructural characterization
GP1c - Transport properties and boundary effects
GP1d - Mechanical properties (including creep)
GP1e - Volume stability
GP1f - Fracture properties and cracking

WG2 - Modeling of CBM and behavior of structures

GP2.a – Microstructural modeling
GP2.b – Multiscale modeling
GP2.c – Macroscopic modeling
GP2.d – Probabilistic modeling
GP2.e – Benchmarking calculations

WG3 - Development of products and recommendations

GP3.a – Development of test equipment / monitoring systems
GP3.b – Development of software and design methods
GP3.c - Development of recommendations and pre-standard methods
GP3.d – Recommendations, pre-standard documents and associated coordination

Contact:

Ole Mejlhede
Send e-mail

Organizing committee:

Miguel Azenha
TBD
O.M. Jensen

21-24
August 2016

Downloads:

Conference brochure (pdf)

Next COST ACTION conference

Materials, Systems and Structures in Civil Engineering

MSSCE 2016

DTU Technical University of Denmark

RILEM

DANISH TECHNOLOGICAL INSTITUTE

- MSSCE 2016 – 3 days – 21-23 August 2016 – MC meeting

8 JAN	Abstract submission
29 JAN	Abstract notification
21 MARCH	Full Paper submission
27 MAY	Paper review notication
8 July	Final paper submission/registration

Conference
21-24
August 2016

CONCREEP-10

September 21-23, 2015 | Vienna, Austria

A- A A+

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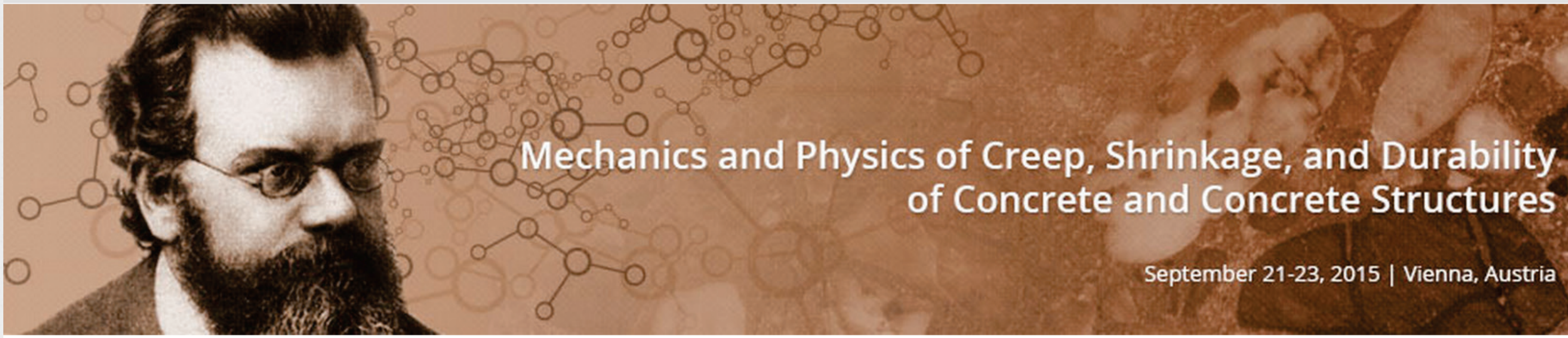
Home   Conference Info ▾   Scientific Programme ▾   Registration & Hotels ▾



Welcome to CONCREEP-10

Enjoy CONCREEP-10!

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