Concrete in Fire: Thermo-Hygro-Mechanical Coupling, Pore Pressure Build-Up, and Material Degradation

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Contents

1. Intro: high temperature behaviour & nuclear safety
2. Thermo-mechanical behaviour (Load-Induced Thermal Strain)
3. Thermal-hygral behaviour (Spalling)
4. Key takeaways & future opportunities

Thermo-mechanics of cementitious materials: nuclear safety

Climate change

- Man-made CO_2 emissions
- Reduction of global emissions
- **Low carbon technologies** for energy production
- Nuclear Power:
  - Developed
  - Reliable
  - Cost effective



Antarctica's melting ice sheets [1]

1. https://www.thetimes.co.uk/article/ice-melt-may-flood-london-by-2100-says-david-attenborough-7j7sf63ds

Nuclear power plants under accidental conditions

- **Concrete material models for high temperatures**
- Concrete containment structures
- Security and safety of society



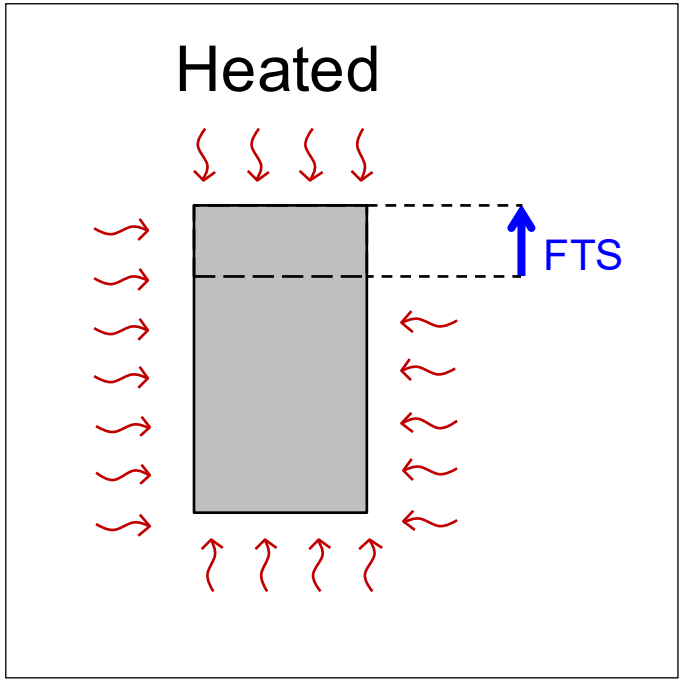
Fukushima nuclear disaster, 2011 [1]

1. EDF Energy. https://www.edfenergy.com/about/research-development/blog/smart-cities

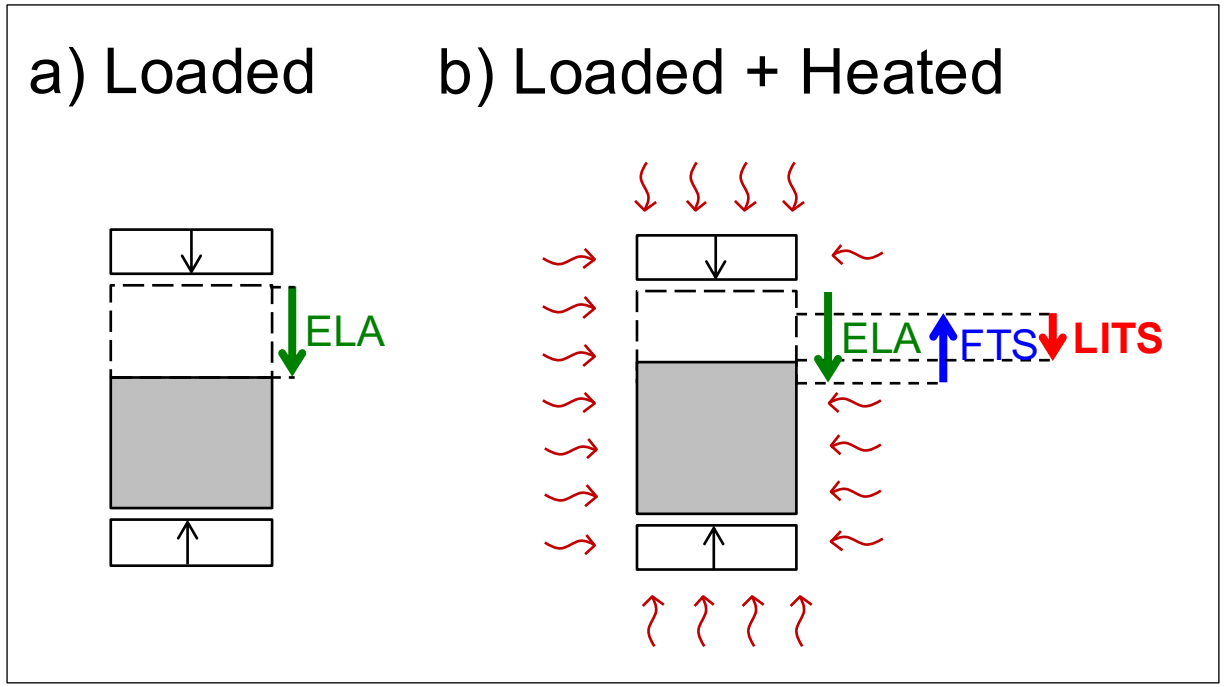
Thermal expansion

Definition of the thermal strain components

- Thermal load
- Stress-free specimen



- Thermal load
- Constant compressive stress



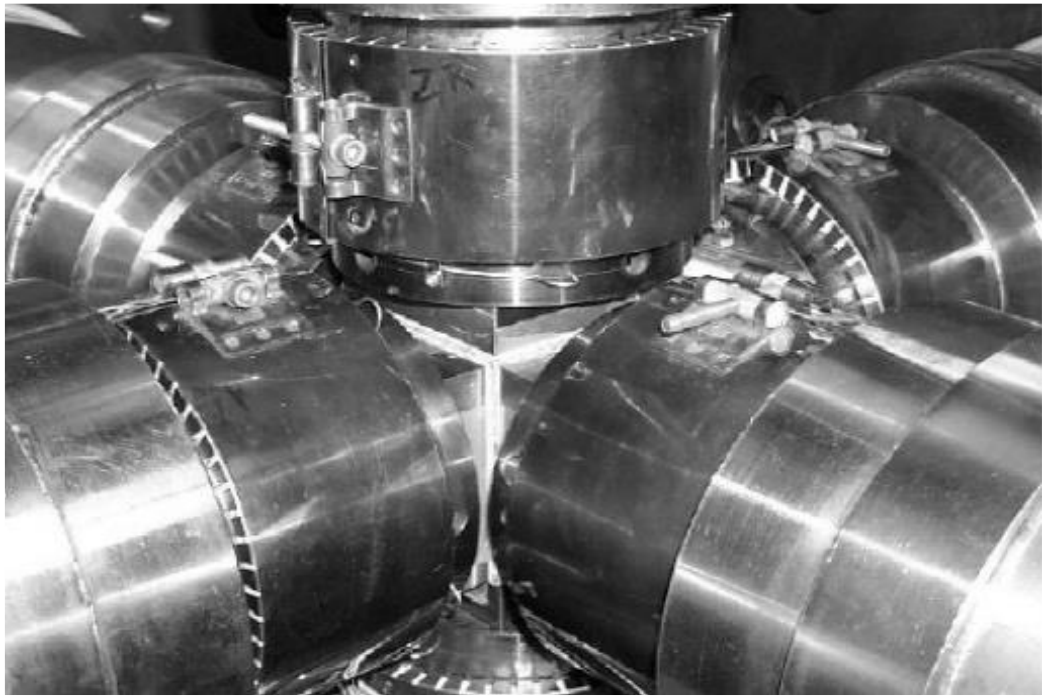
LITS experiments/models

LITS is modelled as independent of:

- Confinement
- Moisture content

LITS grows with:

- Confinement [1]
- Moisture content [2]



Triaxial LITS test [1]

1. Petkovski M, Crouch RS (2008). *Strains under transient hygro-thermal states in concrete loaded in multiaxial compression and heated to 250 °C*. Cement and Concrete Research
2. Khoury, G.A., Grainger, B.N. & Sullivan, P.J.E. (1985). *Strain of concrete during first heating to 600 °C under load*. Magazine of Concrete Research

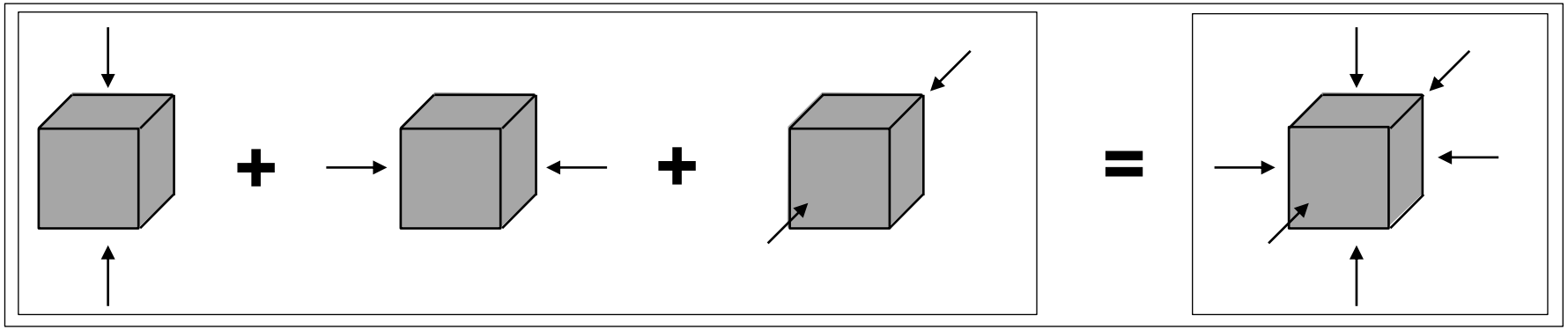
3D extension of uniaxial LITS models

Classic approach[1,2]

$$\dot{\varepsilon}_{ij}^{lits} = \frac{-\upsilon_{lits}\bar{\sigma_{kk}}\delta_{ij} + (1+\upsilon_{lits})\bar{\sigma_{ij}}}{\sigma_{u0}}\,\beta(T)\dot{T}$$

Stress state Temperature

Superposition principle



1. Pearce CJ, Nielsen C V., Bićanić N. (1987) *Gradient enhanced thermo-mechanical damage model for concrete at high temperatures including transient thermal creep*. Int J Numer Anal Methods Geomech 2004
2. Thelandersson S. (1987) *Modeling of combined thermal and mechanical action in concrete*. J Eng Mech

3D extension of uniaxial LITS models

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Stress state Temperature

New paradigm [3]

$$\dot{\varepsilon}_{ij}^{lits} = \eta\,\frac{-\upsilon_{lits}\bar{\sigma_{kk}}\delta_{ij} + (1+\upsilon_{lits})\bar{\sigma_{ij}}}{\sigma_{u0}}\,\beta(T)\dot{T}$$

Confinement Stress state Temperature

$$\eta = 1 + \left(\frac{\bar{\sigma_1} + \bar{\sigma_2} + \bar{\sigma_3}}{\sqrt{(\bar{\sigma_1})^2 + (\bar{\sigma_2})^2 + (\bar{\sigma_3})^2}} - 1\right)\gamma$$

η amplifies LITS in the case of multiaxial compression

3. Torelli, G., Gillie, M., Mandal, P., & Tran, V. X. (2017). A multiaxial load-induced thermal strain constitutive model for concrete. International Journal of Solids and Structures, 108, 115–125. https://doi.org/10.1016/j.ijsolstr.2016.11.017

3D extension of uniaxial LITS models

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New paradigm [3]

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Confinement Stress state Temperature

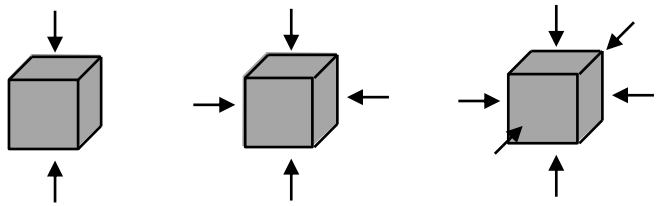
LITS:

- Develops only in compression ($\bar{\sigma_{kk}}$)
- Develops just during the first heating under compressive load (T_{MAX})

3. Torelli, G., Gillie, M., Mandal, P., & Tran, V. X. (2017). A multiaxial load-induced thermal strain constitutive model for concrete. International Journal of Solids and Structures, 108, 115–125. https://doi.org/10.1016/j.ijsolstr.2016.11.017

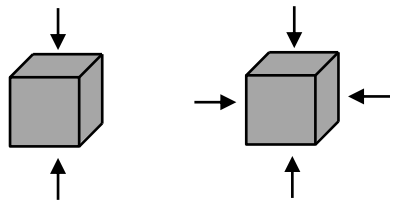
Validation against experiments[1,2]

Petkovski, Crouch [1]



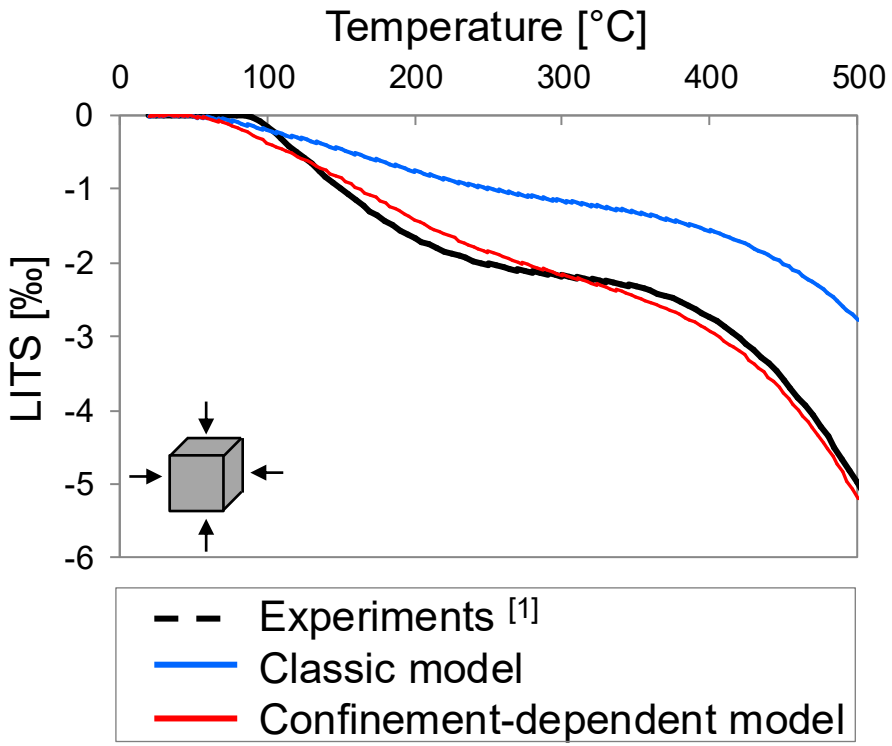
$T \leq 250°C$

Kordina et *al* [2]



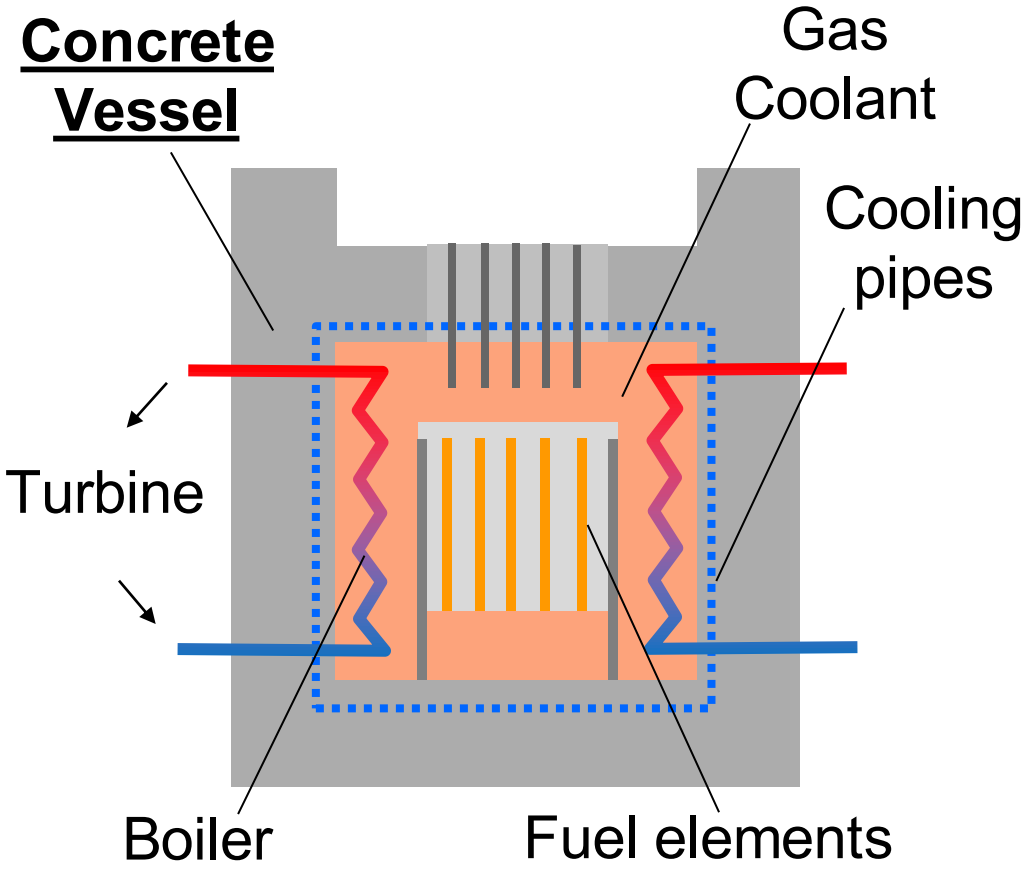
$T \leq 500°C$

LITS under Biaxial compression



1. Petkovski M, Crouch RS (2008). *Strains under transient hygro-thermal states in concrete loaded in multiaxial compression and heated to 250 °C*. Cement and Concrete Research
2. Kordina K, Ehm C, Schneider U. (1986) *Effects Of Biaxial Loading On The High Temperature Behaviour Of Concrete*. Fire Saf Sci

Loss of pre-stress in a nuclear reactor



Service Conditions:

$T_{GAS} \approx 600$ °C

$T_{CONCRETE} \approx 50$ °C

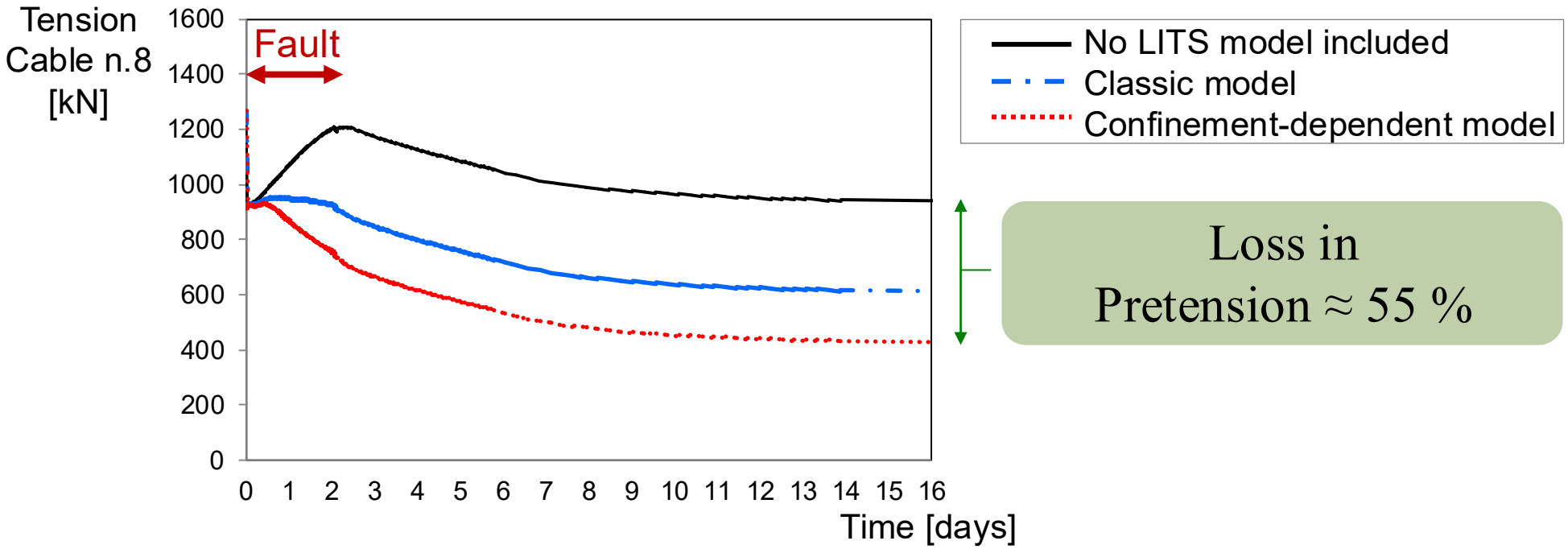
⇩

Accidental Conditions:

$T_{GAS} \approx 600$ °C

$T_{CONCRETE} > 50$ °C

Loss of pre-stress in a nuclear reactor[1]

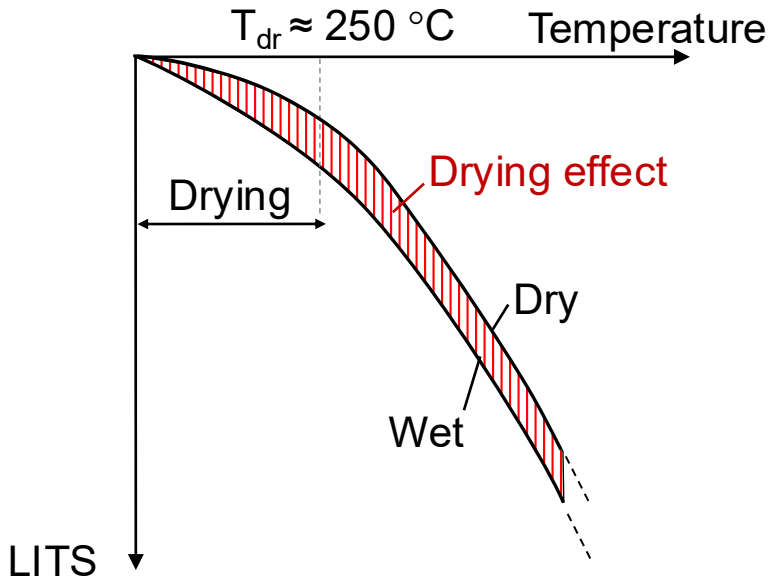


- **The confinement coefficient η** allows capturing the development of LITS in 3D.
- It is essential to include **LITS** in models for assessing reactors under fault conditions.

1. Torelli, G., Gillie, M., Mandal, P., & Tran, V. X. (2017). A multiaxial load-induced thermal strain constitutive model for concrete. International Journal of Solids and Structures, 108, 115–125. https://doi.org/10.1016/j.ijsolstr.2016.11.017

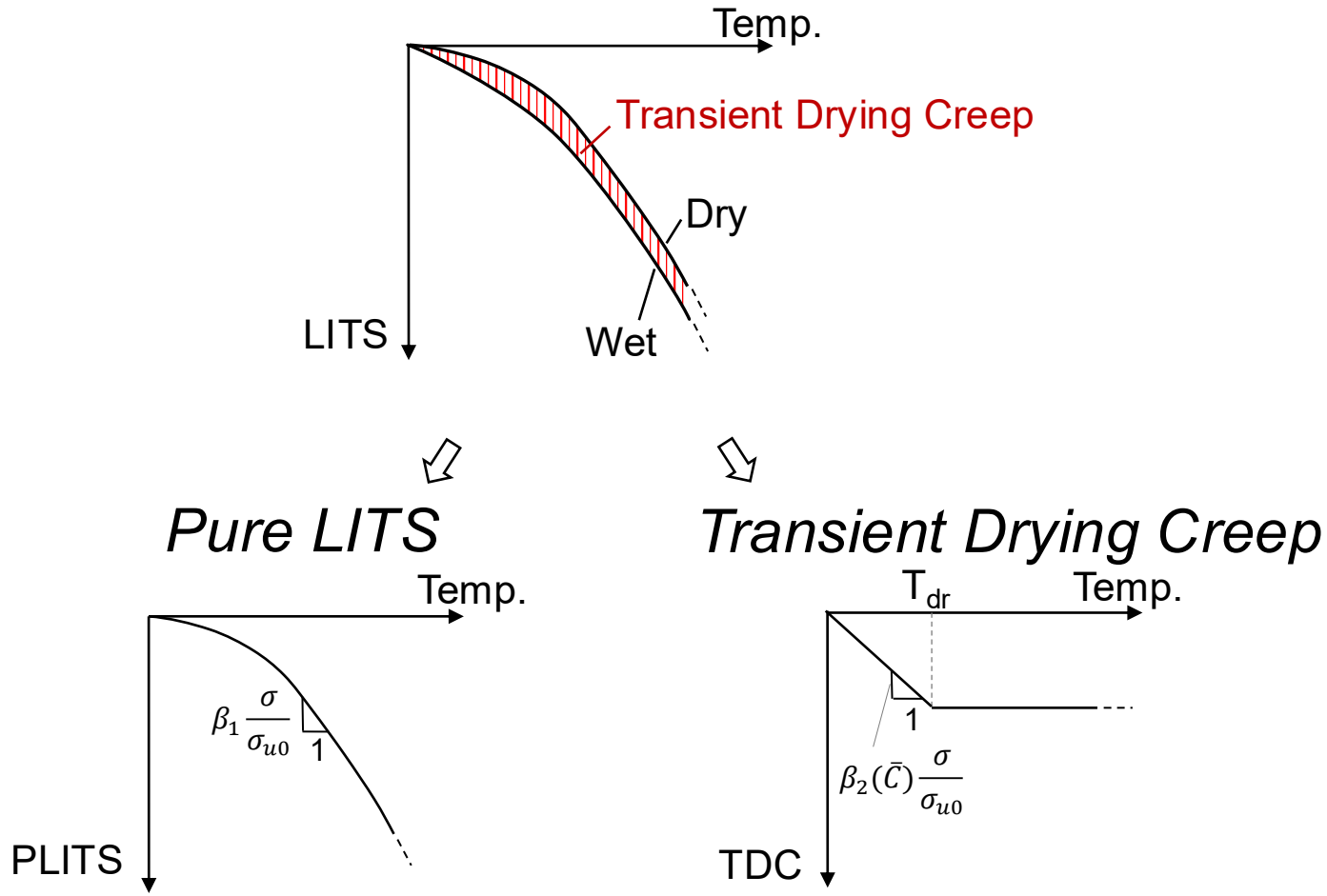
Experimental evidence[1]

↑ Water content ↑ LITS



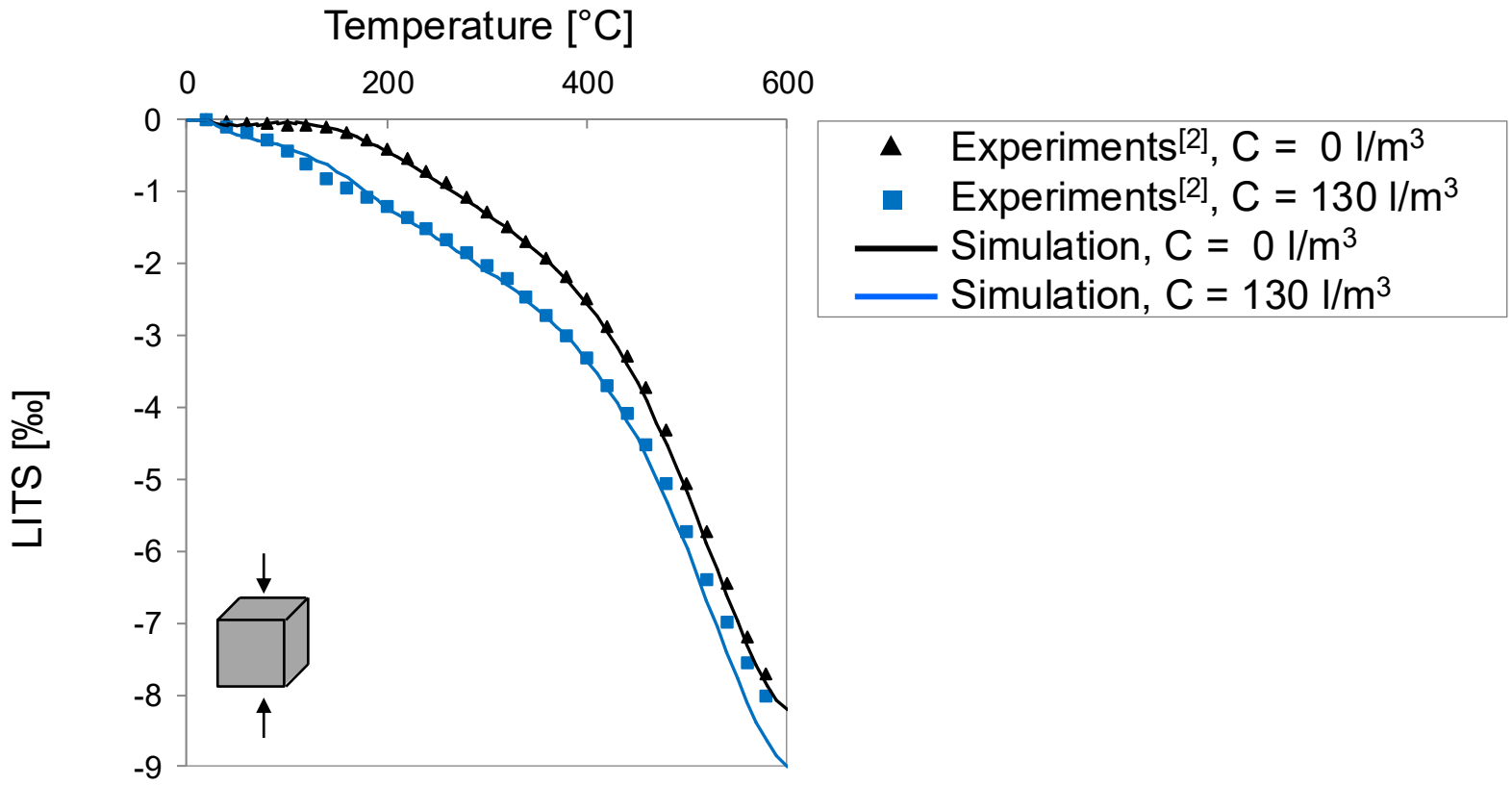
1. Khoury, G.A., Grainger, B.N. & Sullivan, P.J.E. (1985) Strain of concrete during first heating to 600 °C under load. Magazine of Concrete Research

Moisture dependent LITS model[1]



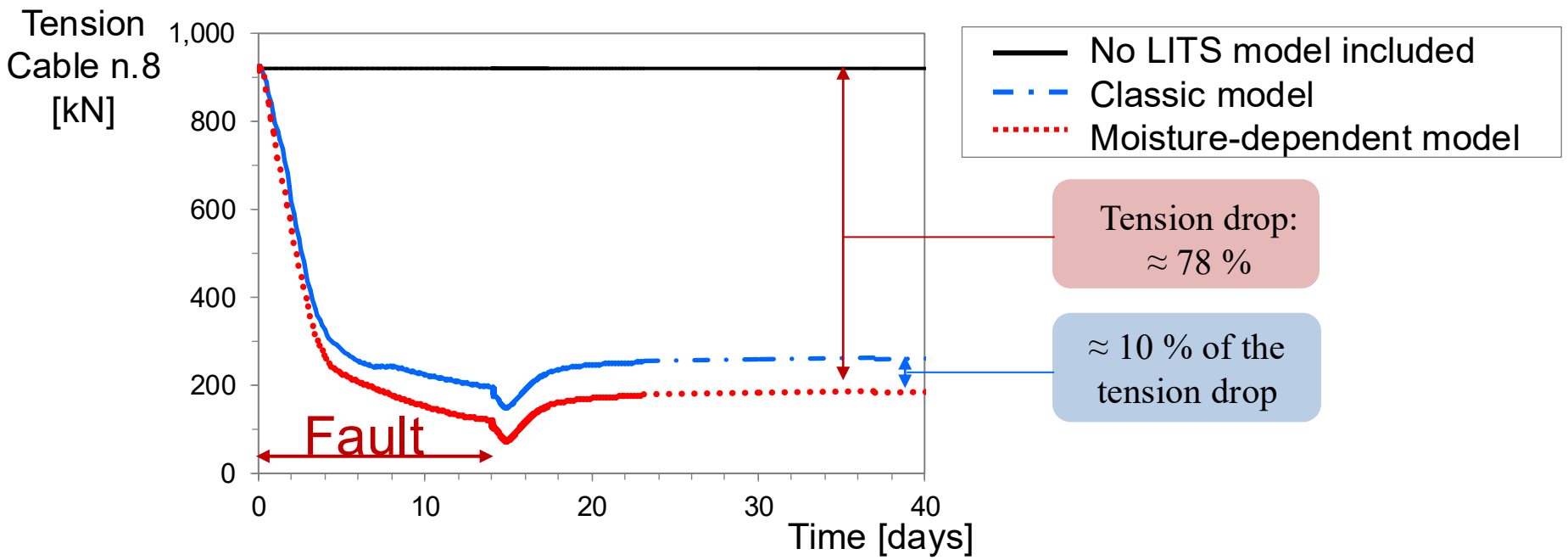
1. *Torelli, G., Gillie, M., Mandal, P., Draup, J., & Tran, V. X. (2020). A moisture-dependent thermomechanical constitutive model for concrete subjected to transient high temperatures. Engineering Structures, 210, 110170. https://doi.org/10.1016/J.ENGSTRUCT.2020.110170*

Validation against experimental results[1]



1. Torelli, G., Gillie, M., Mandal, P., Draup, J., & Tran, V. X. (2020). A moisture-dependent thermomechanical constitutive model for concrete subjected to transient high temperatures. Engineering Structures, 210, 110170.
2. Khoury, G.A., Grainger, B.N. & Sullivan, P.J.E. (1985) Strain of concrete during first heating to 600 °C under load. Magazine of Concrete Research

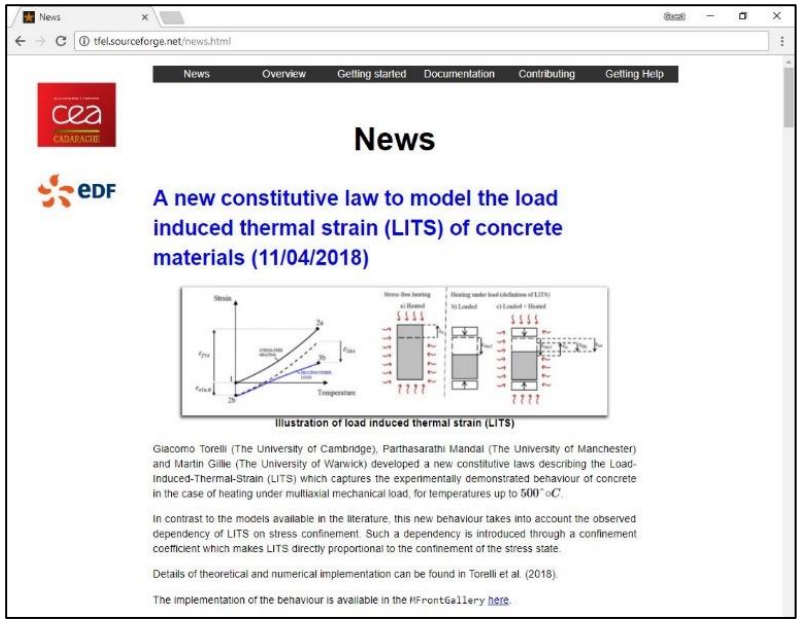
Loss of pre-stress in a nuclear reactor[1]



- The **moisture-dependency** is crucial to capture the actual behavior of heated concrete.
- **Non-conservative results** are obtained if the effect of moisture is neglected.

1. Torelli, G., Gillie, M., Mandal, P., Draup, J., & Tran, V. X. (2020). A moisture-dependent thermomechanical constitutive model for concrete subjected to transient high temperatures. Engineering Structures, 210, 110170.

Impact



http://tfel.sourceforge.net/news.html

- Models[1,2,3,4] used by:
  - *EDF Energy*
  - *CEA* (French Atomic Energy Commission)
- Safety and Security of Society

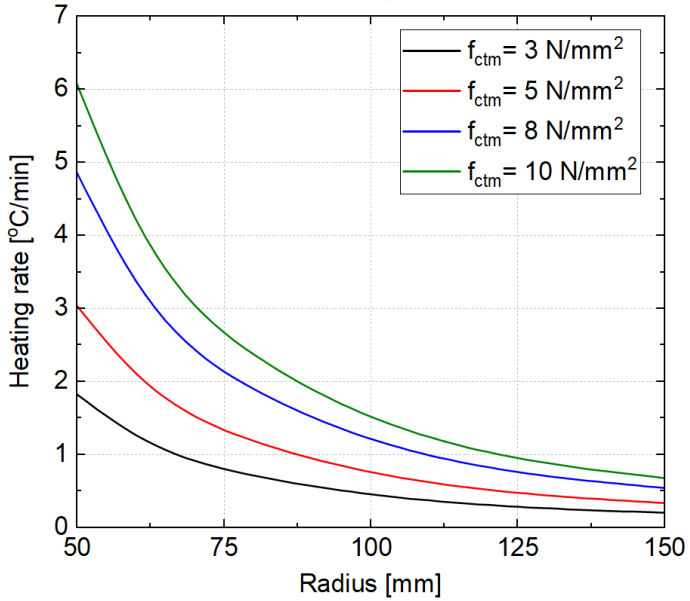
1. Torelli, G., Gillie, M., Mandal, P., & Tran, V. X. (2017). A multiaxial load-induced thermal strain constitutive model for concrete. International Journal of Solids and Structures, 108, 115–125. https://doi.org/10.1016/j.ijsolstr.2016.11.017
2. Torelli, G., Mandal, P., Gillie, M., & Tran, V.-X. (2018). A confinement-dependent load-induced thermal strain constitutive model for concrete subjected to temperatures up to 500 °C. International Journal of Mechanical Sciences, 144, 887–896. https://doi.org/10.1016/j.ijmecsci.2017.12.054
3. Draup, J., Gangnant, A., Colette, G., Doughty, G., Guo, J., Helfer, T., Torelli, G., & Mandal, P. (2019). Development of a novel damage model for concrete subjected to high temperature and constraint. Proceedings of the 25th International Conference on Structural Mechanics in Reactors Technology - SMiRT25., Division 1-Session 1-Paper 5.
4. Torelli, G., Gillie, M., Mandal, P., Draup, J., & Tran, V. X. (2020). A moisture-dependent thermomechanical constitutive model for concrete subjected to transient high temperatures. Engineering Structures, 210, 110170.

Transient test methodology[1]

Reducing uncertainty associated with:

- Thermal gradients
- Strain measurement technique

Test design chart



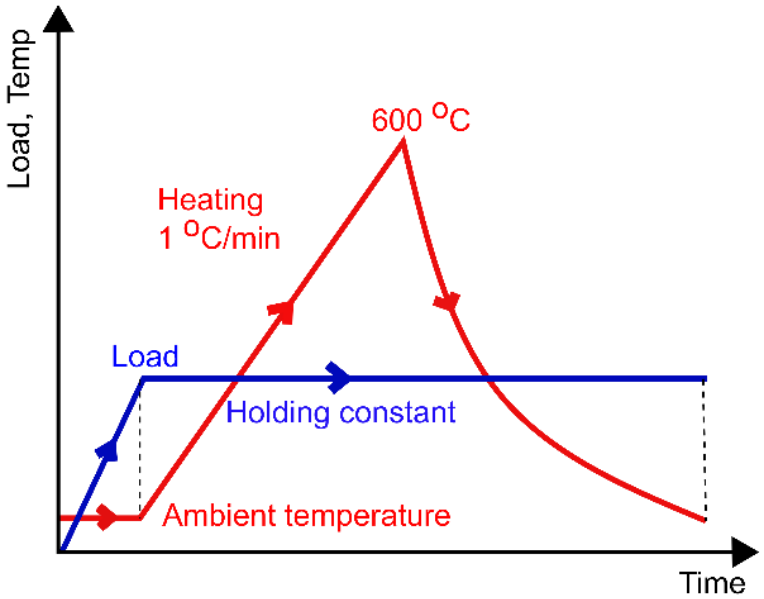
Test setup



1. Selvaranjan, K., Provis, J. L., Guadagnini, M., & Torelli, G. (2025). Apparatus for measuring concrete deformation under constant load at transient elevated temperature. Construction and Building Materials, 494, 142989. https://doi.org/10.1016/J.CONBUILDMAT.2025.142989

Coarse aggregate: size distribution & volume fraction

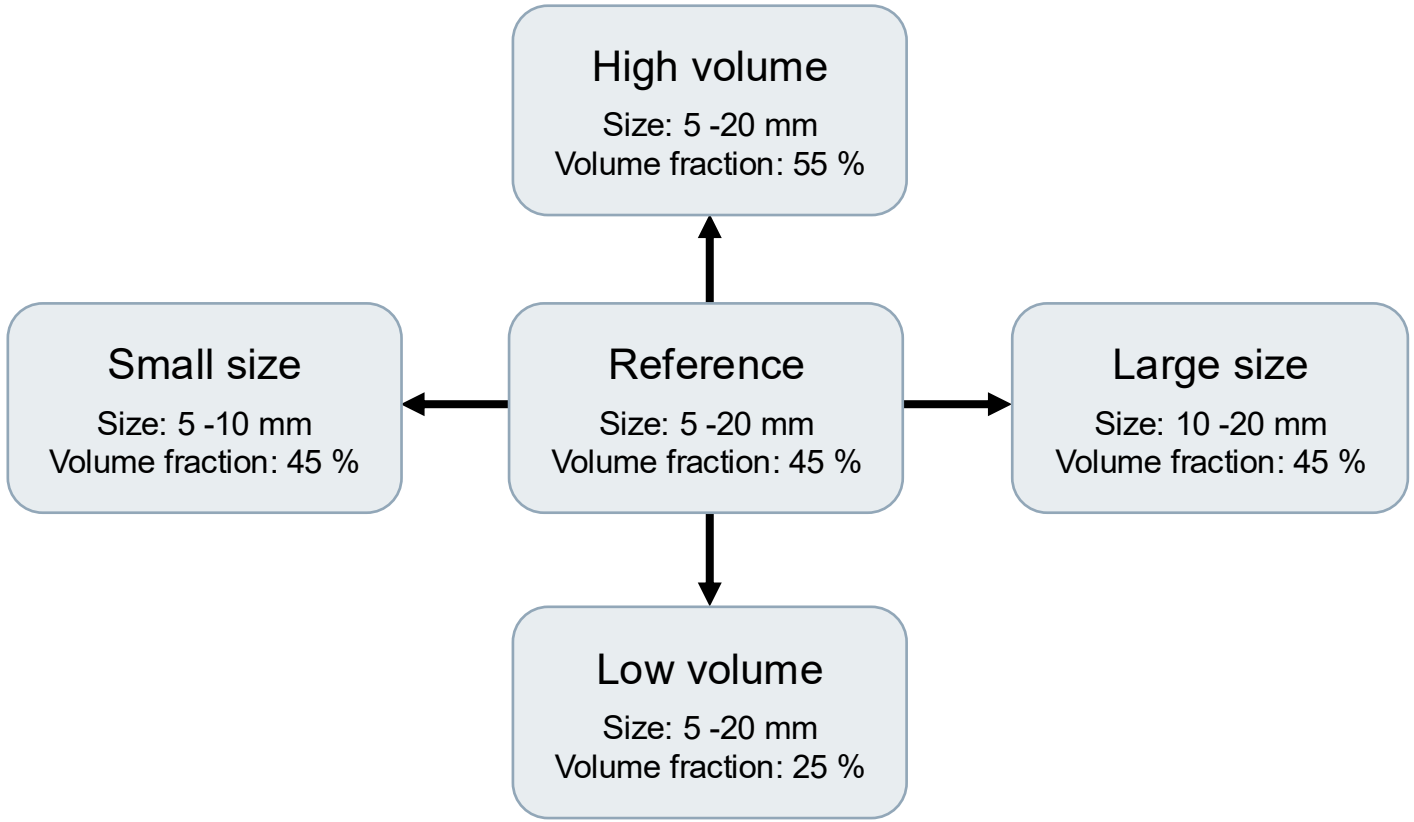
Thermomechanical load



Load levels

20%, 40%, 60%, and 80% of f_{cm}

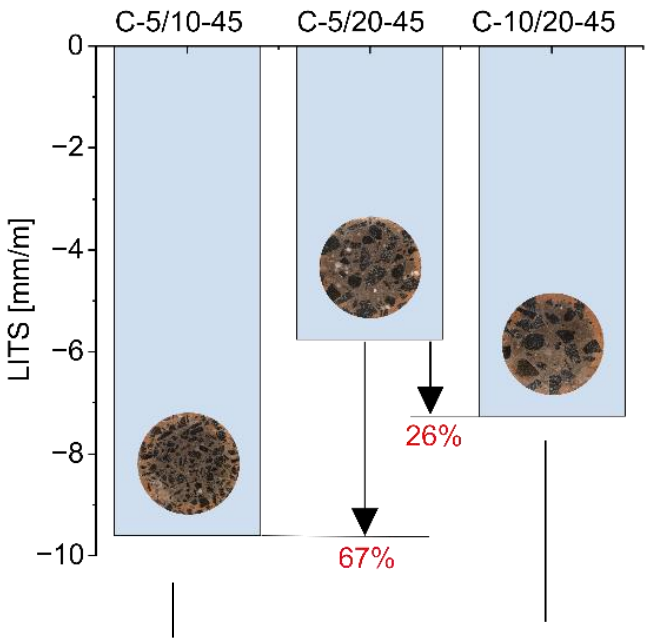
Concrete mixes



1. Selvaranjan, K., Provis, J. L., Guadagnini, M., & Torelli, G. (2024, August). Effect of aggregate size on load induced thermal strain of concrete at high temperature. 78th RILEM Annual Week & RILEM Conference on Sustainable Materials & Structures: Meeting the Major Challenges of the 21st Century - SMS 2024.

Coarse aggregate: size distribution & volume fraction

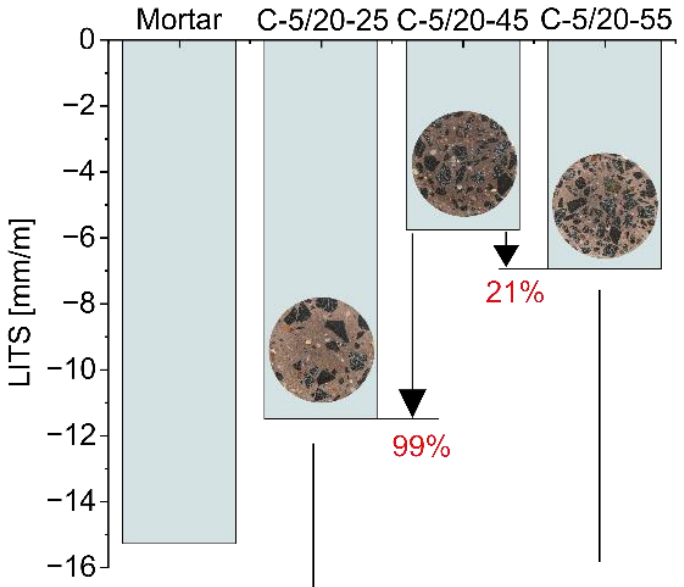
Size of aggregate



High ITZ volume fraction

High interface stress

Aggregate volume fraction



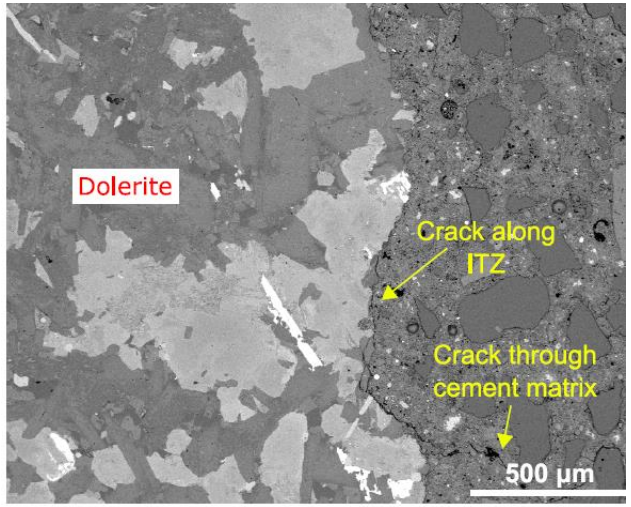
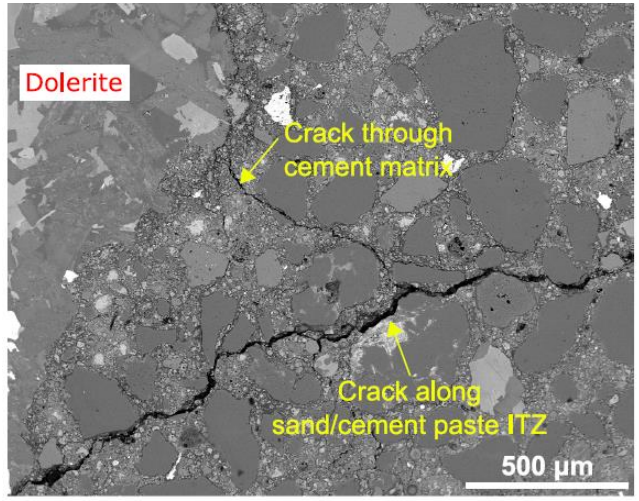
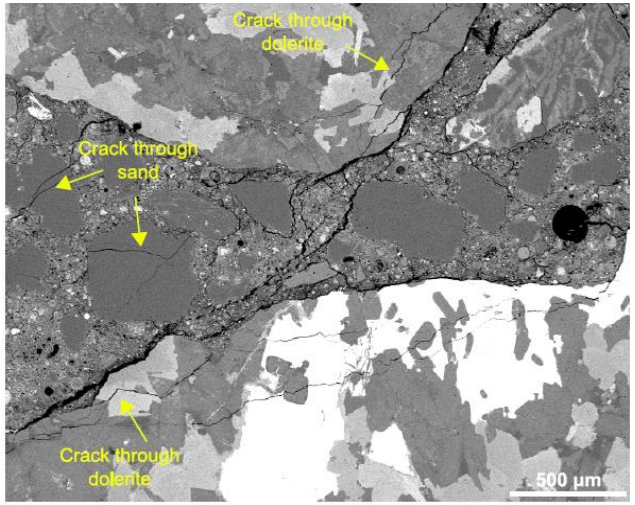
Low restraints

High ITZ volume fraction

Impact:

Informing assessment & design

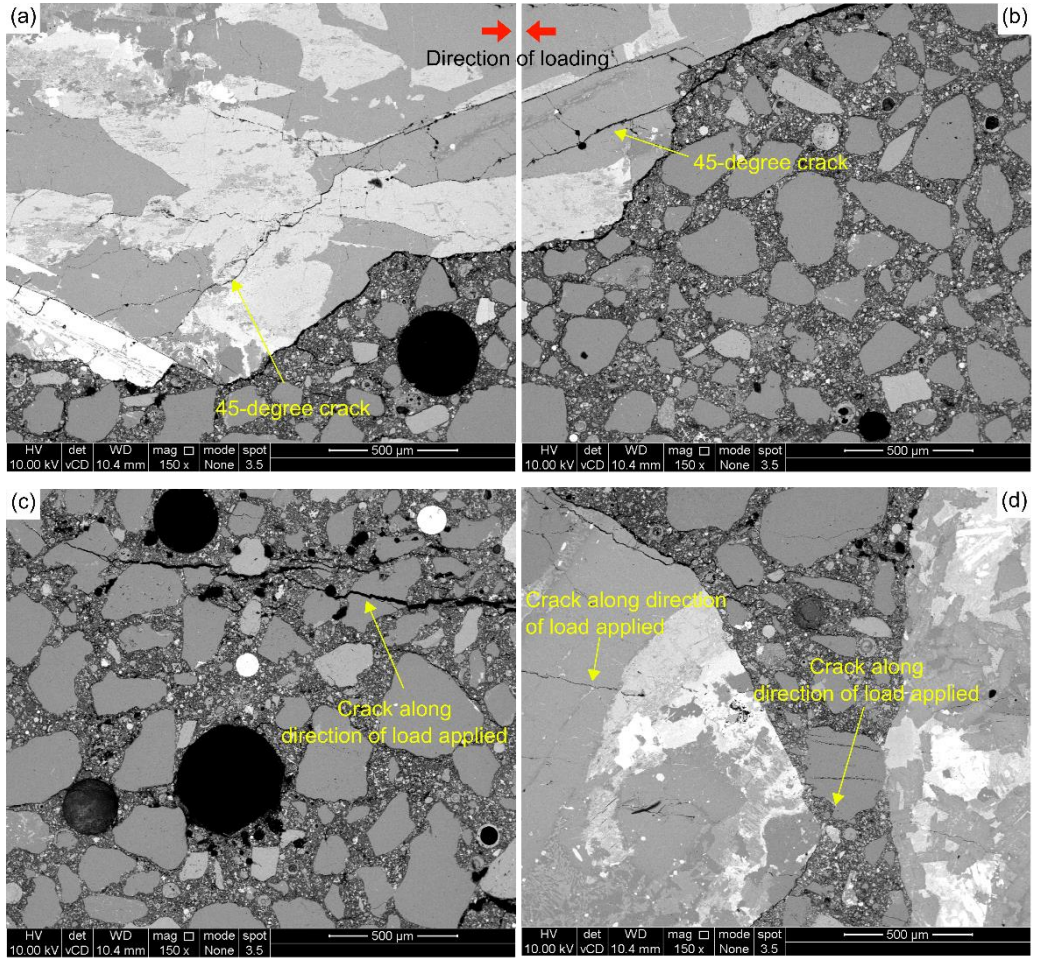
Physical origins: microcracking[1]

	Loaded-only (40% fc)	Heated-only (600°C)	Loaded + Heated (40% fc, 600°C)
BSE image			
ITZ cracking	Minor	Moderate	Extensive
Mortar cracking	Minor	Moderate	Extensive
Aggregate cracking	-	-	Extensive

1. Selvaranjan, K., Provis, J. L., Guadagnini, M., & Torelli, G. (2025). Role of coarse aggregate restraint on the load induced thermal micro-cracking of concrete. In preparation.

Physical origins: microcracking

Cracks parallel to the load



Impact:

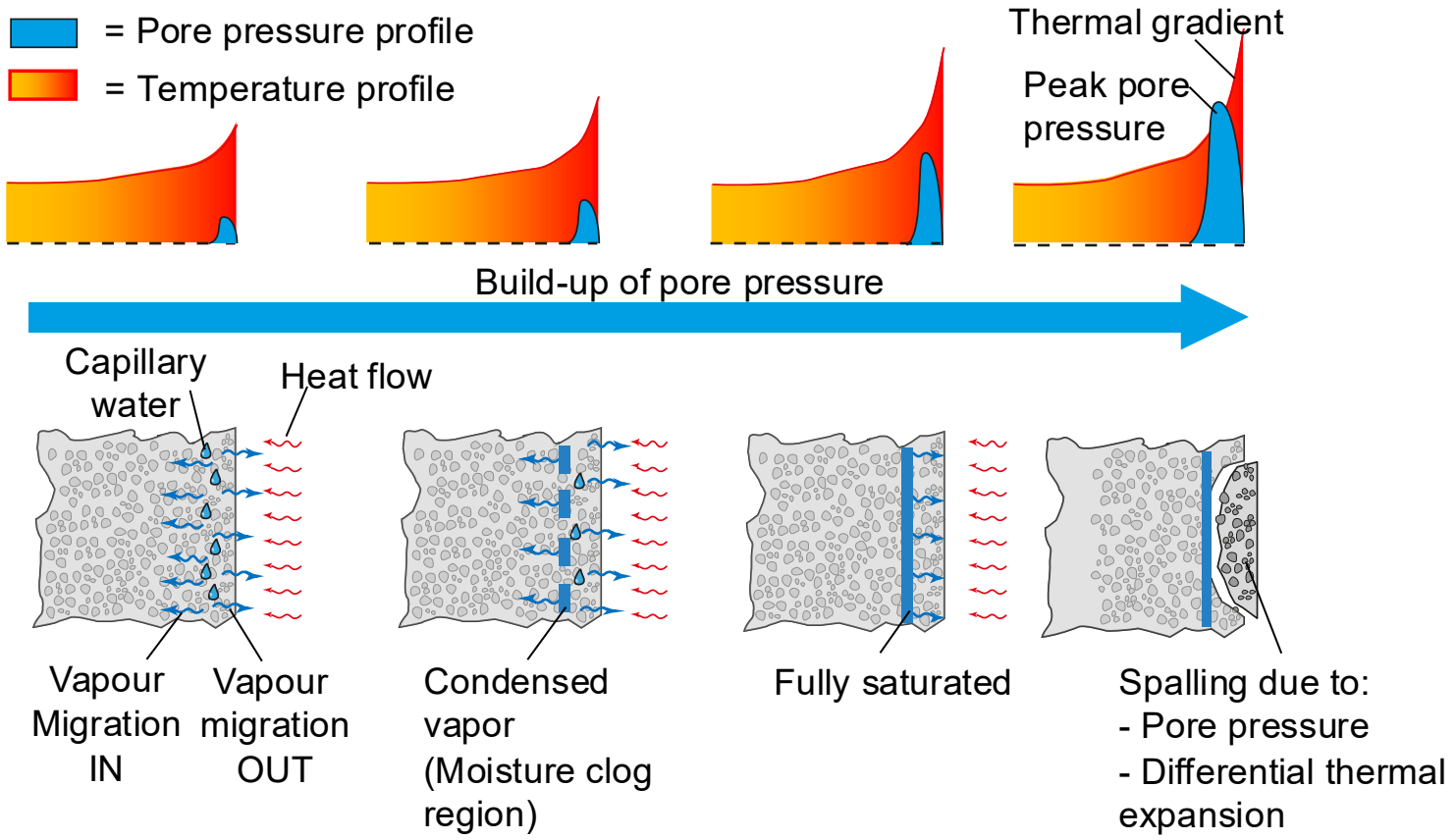
- Physical origin of LITS Poisson's ratio
- Increased confidence in our confinement dependent LITS models

High temperature spalling

High temperature spalling

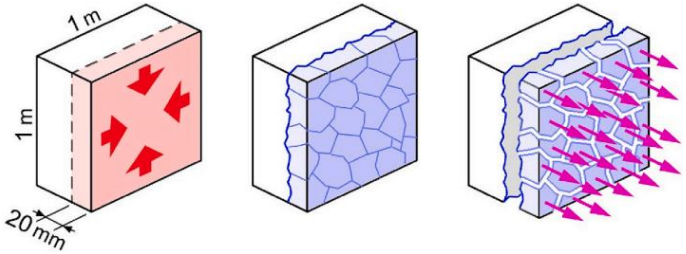
Crack initiation

Pore Pressure + Differential thermal expansion



Crack propagation

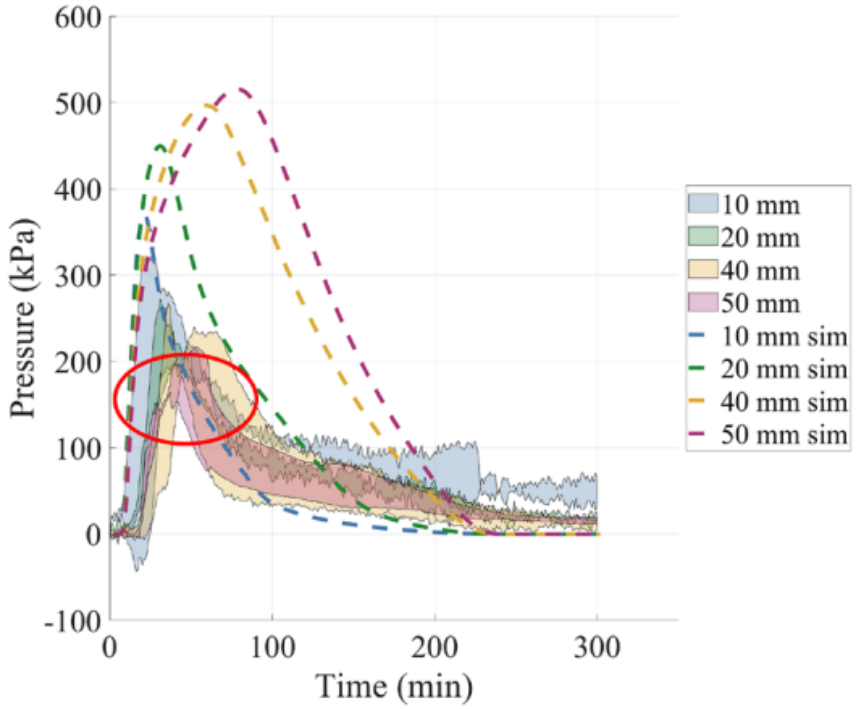
Accumulated thermal energy[1]



[1] Felicetti, R., Yarmohammadian, R., Pont, S. D., & Tengattini, A. (2024). Fast vapour migration next to a depressurizing interface: A possible driving mechanism of explosive spalling revealed by neutron imaging.

The pore pressure challenge

Measured vs. Simulated Pore Pressure[1]

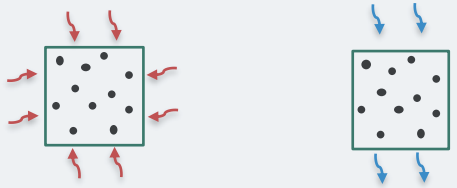


High-fidelity simulations overpredict pressures.

1. Riitamaa, C., Markert, F., Giuliani, L., & Hostikka, S. (2025). Heat and Mass Transfer Model for Fire-Exposed Concrete—Part A: Validation of Temperature and Pressure Predictions. International Journal of Concrete Structures and Materials, 19(1), 88. https://doi.org/10.1186/s40069-025-00828-7

Predictive modelling

Material Characterization

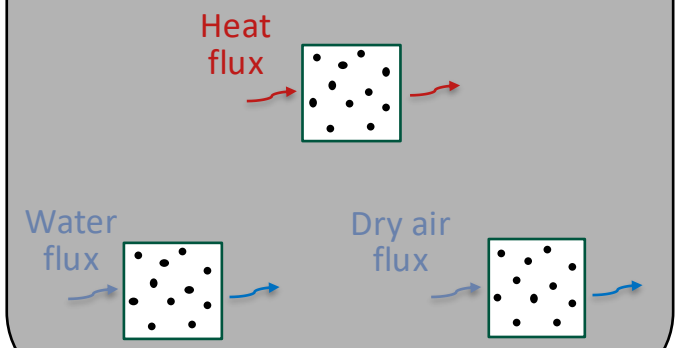


Material Parameters

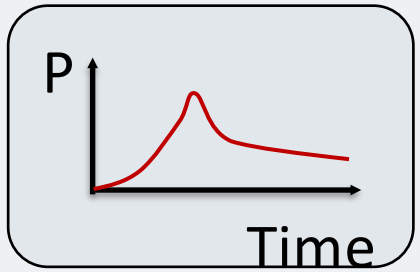
$\varphi_0,\ K_0,\ C_{ps_0},\ \lambda_d$

Validation process

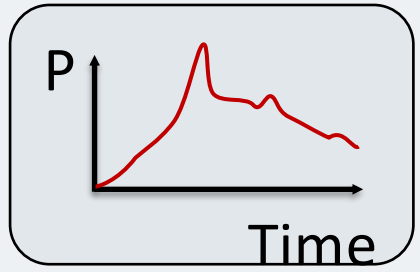
Model



Predicted Pore Pressure

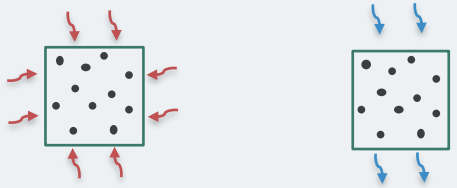


Measured Pore Pressure



Predictive modelling

Material Characterization

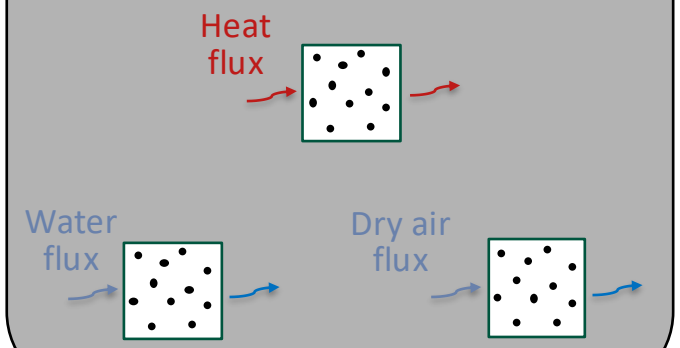


Material Parameters

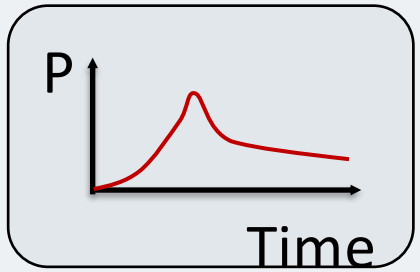
$\varphi_0,\ K_0,\ C_{ps_0},\ \lambda_d$

Validation process

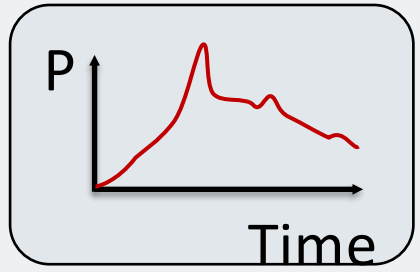
Model



Predicted Pore Pressure



Measured Pore Pressure



Statical analyses on thermal-hygral model

Thermal	Hygral	Mechanical
Heat Transfer	Mass Transport	Momentum Balance
		Fracture Evolution
Energy Balance	Mass Balance	
⇩	⇩	⇩
Temperature Profiles	Pressure Profiles	Spalling

Modelling assumptions

Concrete is a partially saturated porous medium

Solid Phase

- Cement Paste
- Aggregates

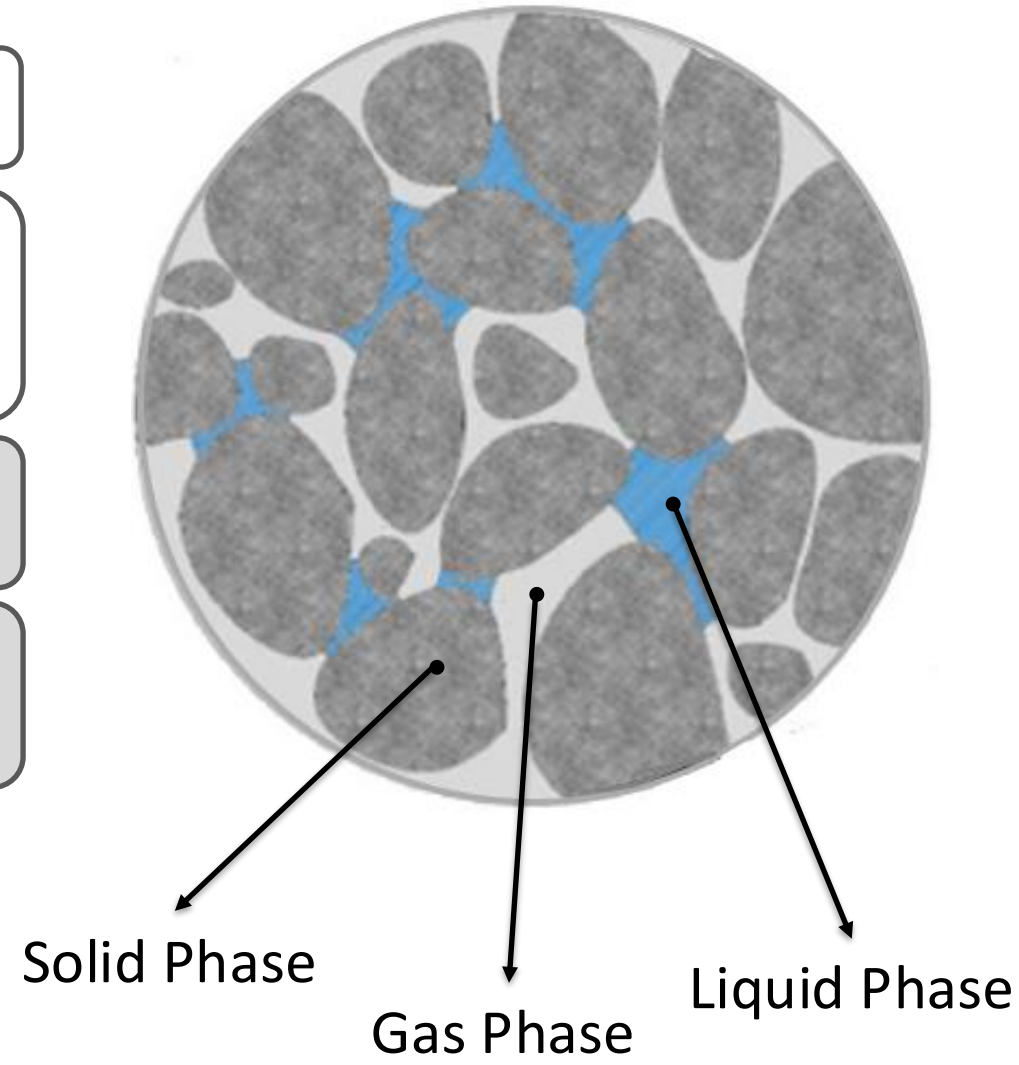
Liquid Phase

- Pore Water

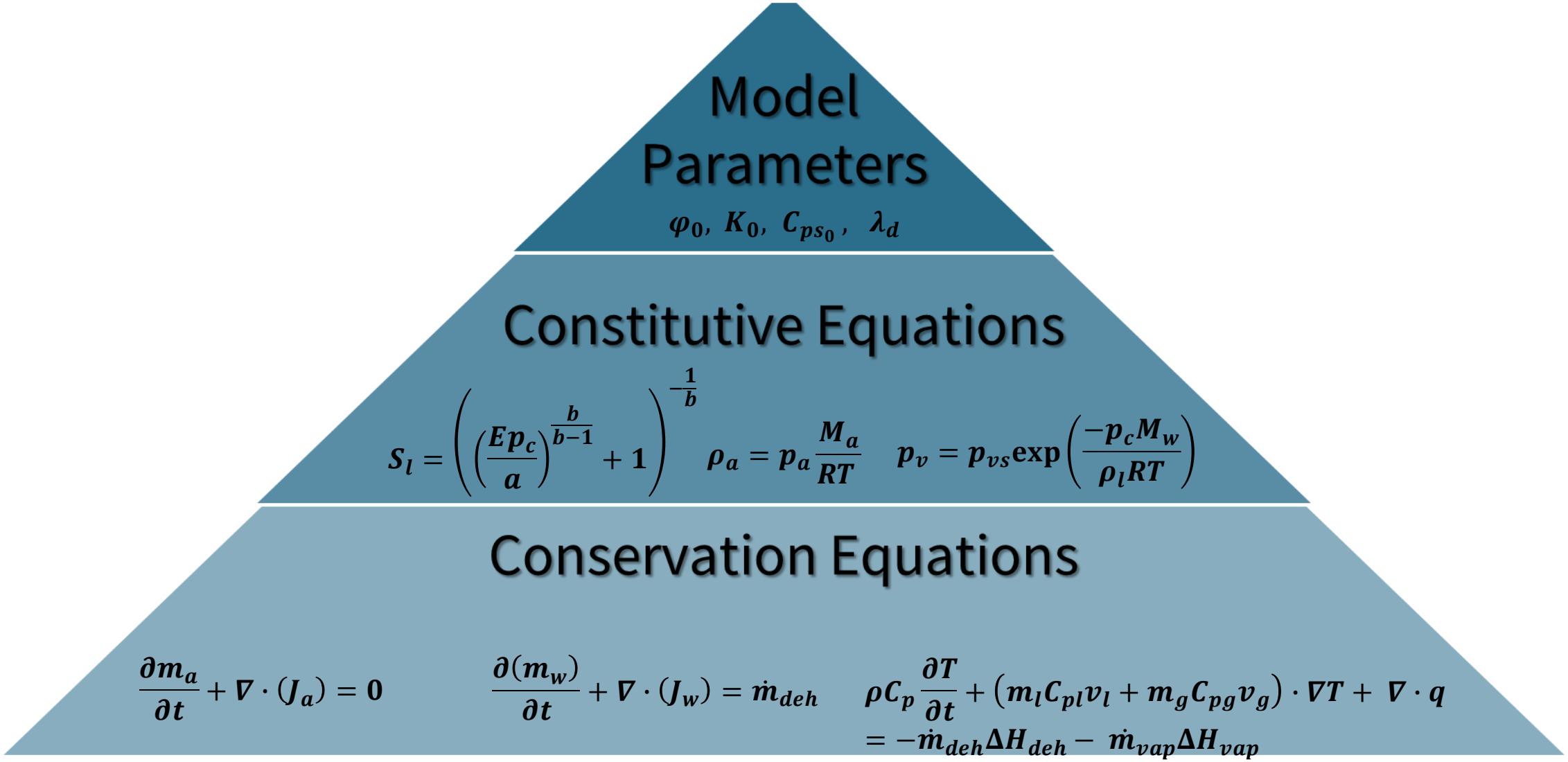
Gas Phase Components

- Dry Air
- Water Vapour

(Pesavento, 2000)



Structure of the developed numerical model



Equations Describing the Heat and Mass Transfer in Concrete

1. Mass Conservation for **Dry Air**

$$\frac{\partial(\varphi(1-S_l)\rho_a)}{\partial t} + \nabla \cdot (m_a v_a) = 0$$

2. Mass Conservation for **Water Species** (Liquid Water & Water Vapour)

$$\frac{\partial \varphi(S_l\rho_l + (1-S_l)\rho_v)}{\partial t} + \nabla \cdot (m_l v_l + m_v v_v) = -\ \dot{m}_{deh}$$

3. Conservation of **Energy**

$$\rho C_p \frac{\partial T}{\partial t} + \left(m_l C_{pl} v_l + m_g C_{pg} v_g\right) \cdot \nabla T + \nabla \cdot (-\lambda \cdot \nabla T) = \dot{m}_{deh}\Delta H_{deh} - \dot{m}_{vap}\Delta H_{vap}$$

An example

System unknowns

Physical parameters

Material parameters

- Understand impact
- Guide characterization

Mass Conservation of Dry Air

$$\frac{\partial \bar{\rho}_a}{\partial t} + \nabla \cdot (\boldsymbol{J}_a) = 0$$

$$\bar{\rho}_a = \varphi(1 - S_l)\rho_a$$

$$\rho_a = p_a \frac{M_a}{RT}$$ Ideal Gas Law

$$\varphi = \varphi_0 + A_\varphi (T - T_0) \quad [7]$$

$$S_l = \left(\left(\frac{E p_c}{a} \right)^{\frac{b}{b-1}} + 1 \right)^{-\frac{1}{b}} \quad [8]$$

$$E = \begin{cases} \left(\frac{T_{crit} - T_0}{T_{crit} - T} \right)^N, & T < T_{crit} \\ \frac{N}{Z} E_0 T + \left(E_0 - \frac{N}{Z} E_0 (T_{crit} - Z) \right), & T \geq T_{crit} \end{cases}$$

$$a = \begin{cases} q_3, & T < 100°C \\ q_1 + q_2, & T \geq 100°C \end{cases}$$

$$p_a = p_g - p_v$$ Dalton's Law

$$p_v = p_{vs} \exp\left(\frac{-p_c M_w}{\rho_l R T} \right)$$ Kelvin's Equation

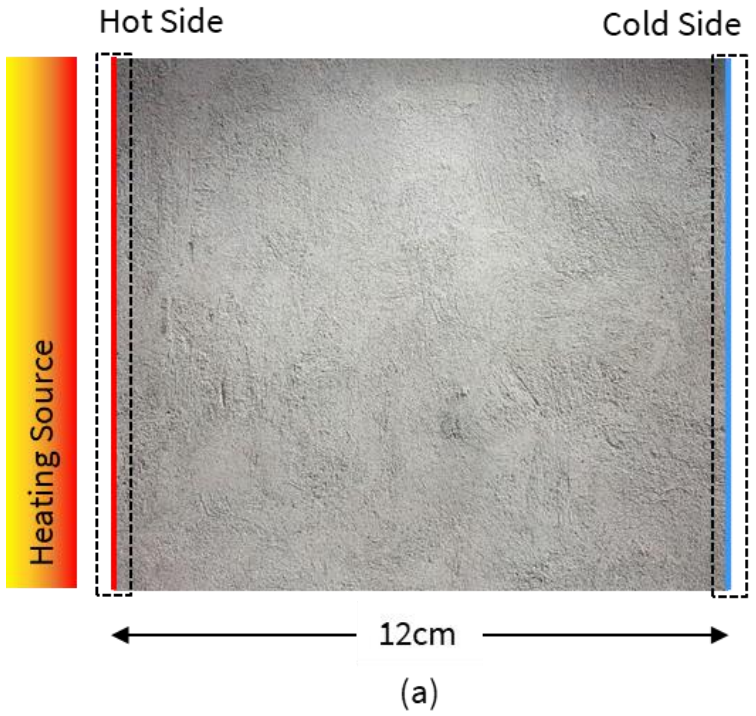
$$q_1 = (q_3 - q_2) \left(1 + 2 \left(\frac{T - T_B}{T_{crit} - T_B} \right)^3 - 3 \left(\frac{T - T_B}{T_{crit} - T_B} \right) \right)$$

$$p_{vs} = \exp\left[\frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 \ln(T) \right] \quad [9]$$

$$\rho_l = (b_0 + b_1 T + b_2 T^2 + b_3 T^3 + b_4 T^4 + b_5 T^5) + (p_{l-1} - p_{l-2})(a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5) \quad [10]$$

The problem

1D geometry



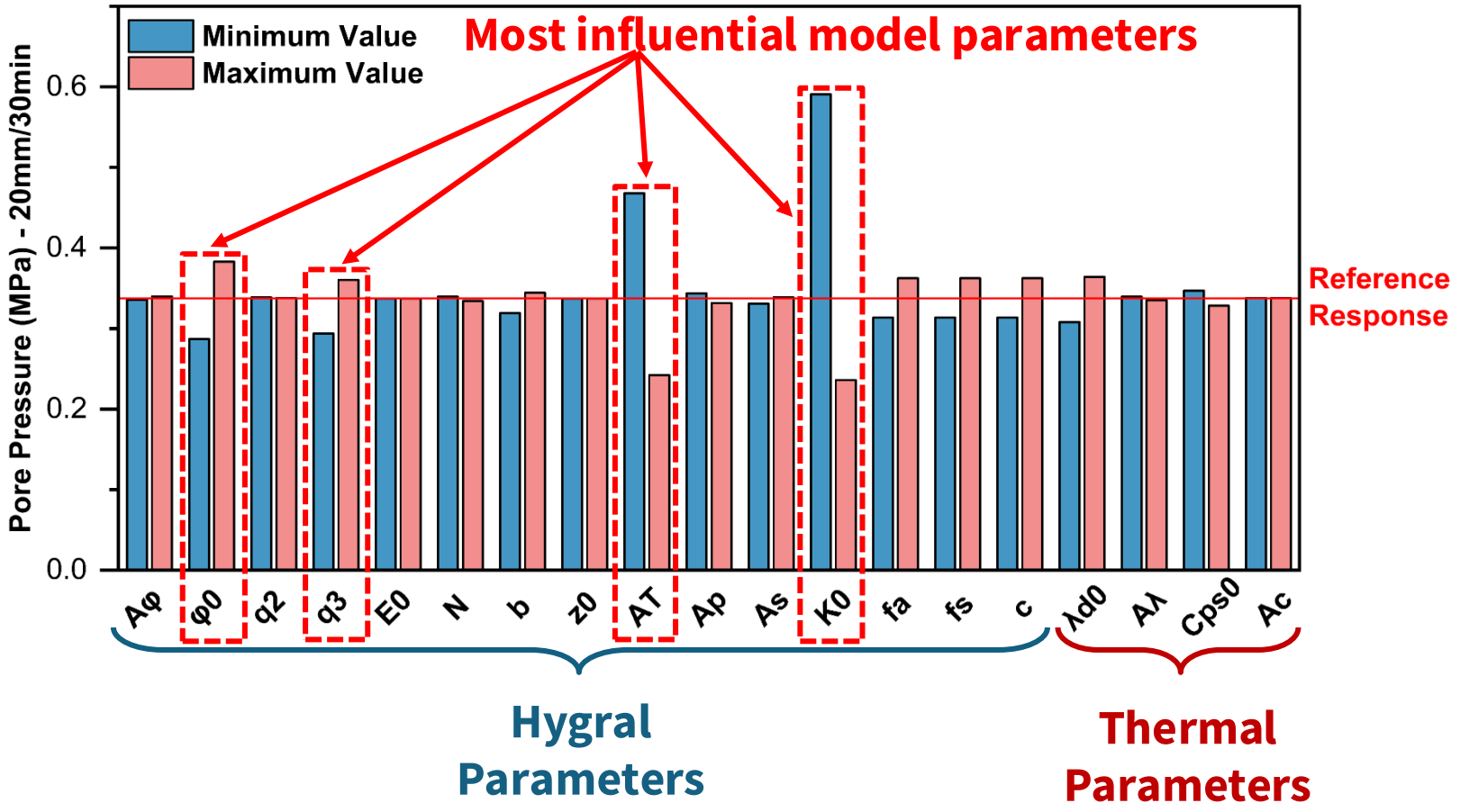
ISO-834 fire curve

Initial and boundary conditions

Transport Process	Boundary Condition Type	Hot Boundary	Cold Boundary	Initial Conditions
Heat Transfer	Dirichlet	$T_{heating}$	$T_{ambient}$	$T_{ambient}$
Mass Transport of Gas	Dirichlet	$p_{atmospheric}$	$p_{atmospheric}$	$p_{atmospheric}$
Mass Transport of Vapour	Neuman	$-h_{g\ hot}(\rho_v - \rho_v^{\infty})$	$-h_{g\ cold}(\rho_v - \rho_v^{\infty})$	$\frac{\rho_{l_0} R T_{amb} loglog\ (RH_{ini})}{M_w}$

Material Parameters	Symbol	Unit	Reference Values	CV (%)	
Thermal Conductivity	λ_{d0}	W/(m·K)	2	20	Thermal Parameters
Thermal Conductivity Coefficient	A_λ	1/K	0.0005085	10	
Heat Capacity	C_{ps0}	J/(kg·K)	950	10	
Heat Capacity Coefficient	A_c	1/K	0.00037	10	
Porosity Coefficient	A_ϕ	1/K	0.000195	20	Hygral Parameters
Initial Porosity	ϕ_0	%	0.04	50	
Liquid Saturation Coefficients at Ambient and High Temperatures	q_2	Pa	7000000	50	
	q_3	Pa	46936400	50	
	E_0	-	1	10	
	N	-	1	25	
	b	-	2.0601	10	
	z_0	K	5	10	
Permeability Coefficients at Ambient and High Temperatures	A_T	-	0.005	10	
	A_p	-	0.368	10	
	A_s	-	0.6605	10	
Intrinsic Permeability	K_0	m^2	10^{-17}	50	
Age of Concrete	f_a	-	0.85	10	
Stoichiometric Factor	f_s	-	0.24	10	
Cement Mass	c	kg/m^3	580	10	

Statistical analysis



Intrinsic Permeability of Concrete (Gawin, 1999):

$$K = \boldsymbol{K_0} 10^{\boldsymbol{A_T}(T-T_0)} \left(\frac{p_g}{p_{atm}}\right)^{A_p}$$

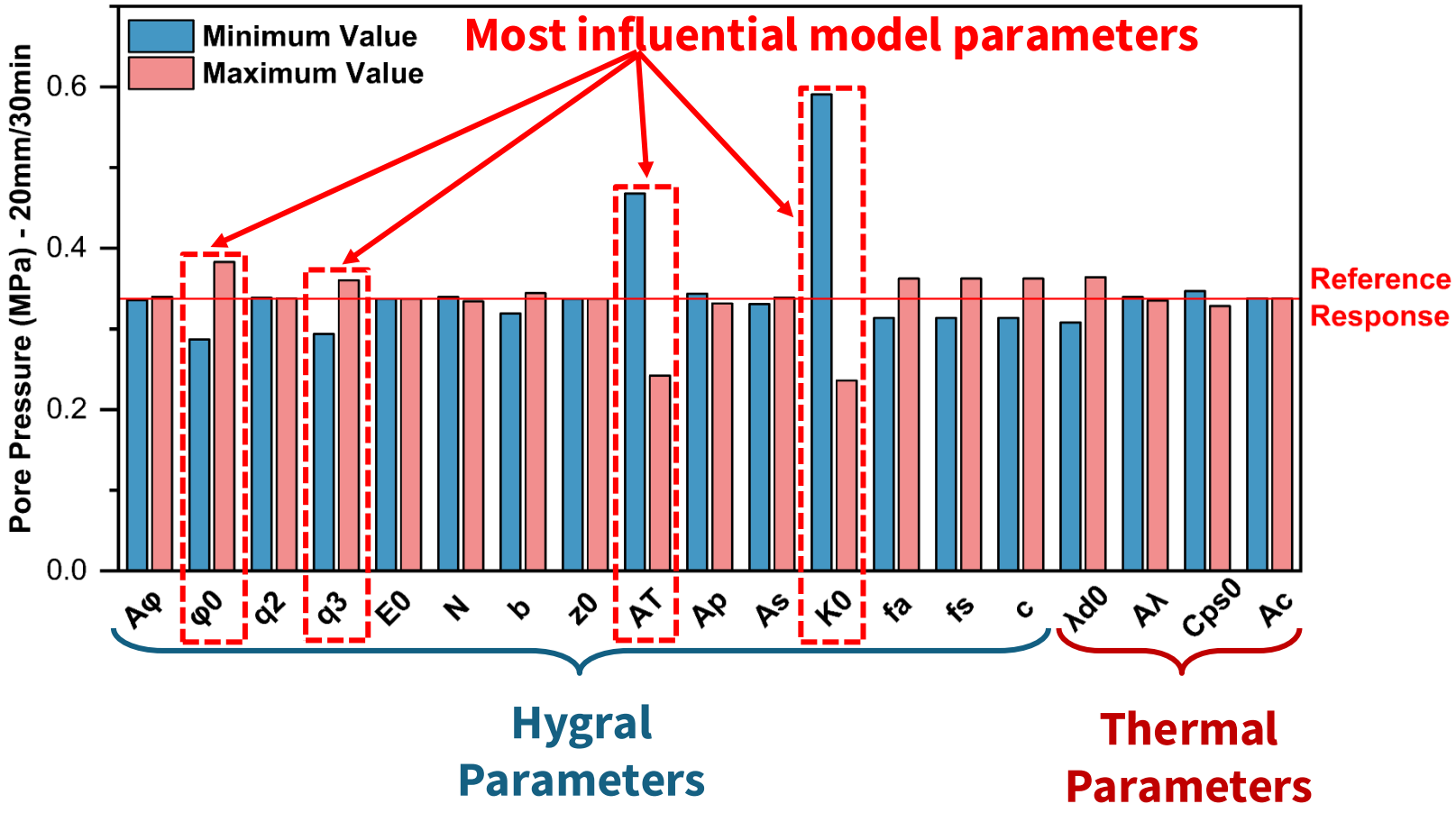
Increase for high pressures

Increase for high temperatures

Permeability at:

- Ambient temperature
- Atmospheric pressure

Statistical analysis



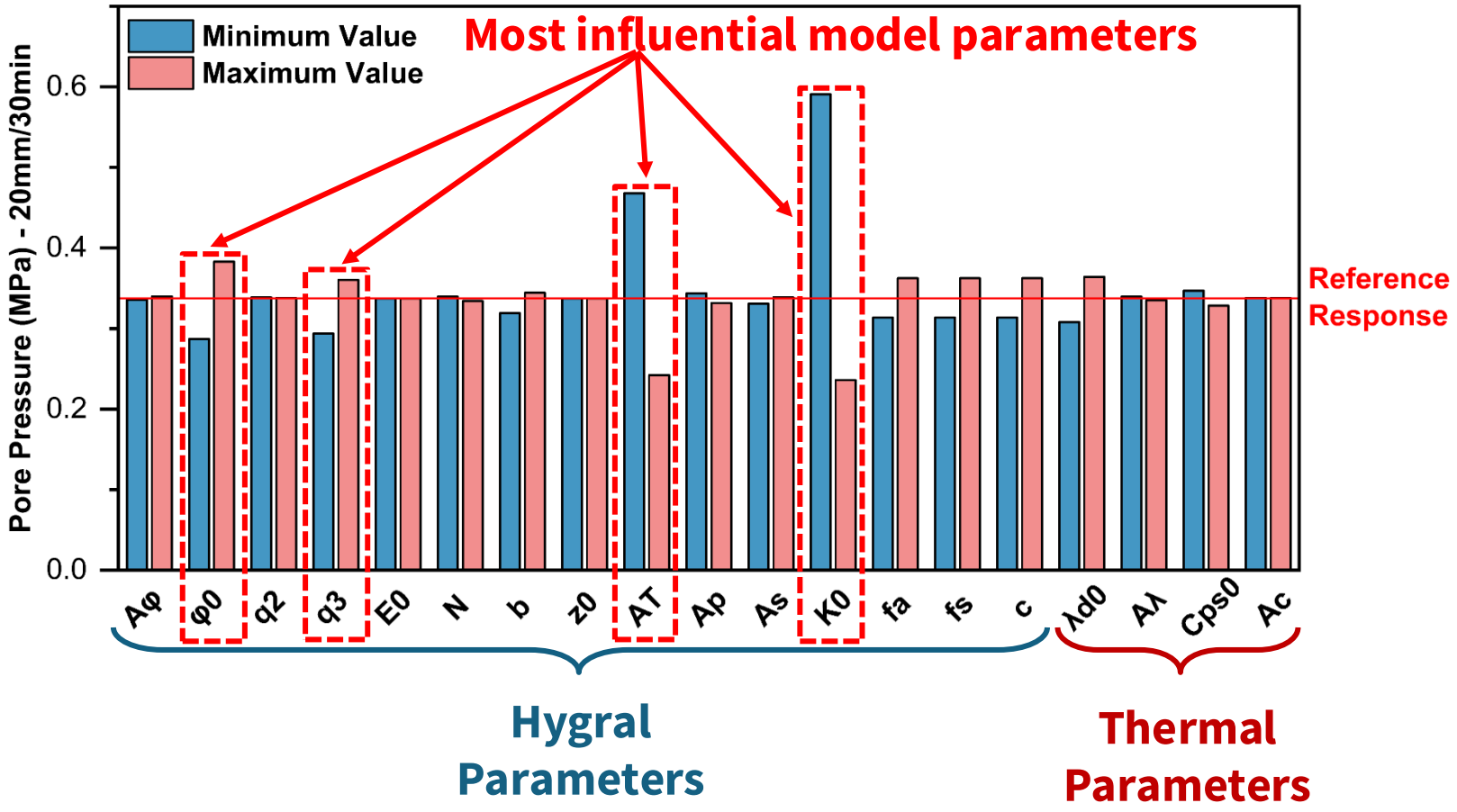
Porosity (Schneider and Herbst, 1989):

$$\varphi = \boldsymbol{\varphi_0} + A_\varphi (T - T_{amb})$$

Porosity at ambient temperature

Increase for high temperatures

Statistical analysis



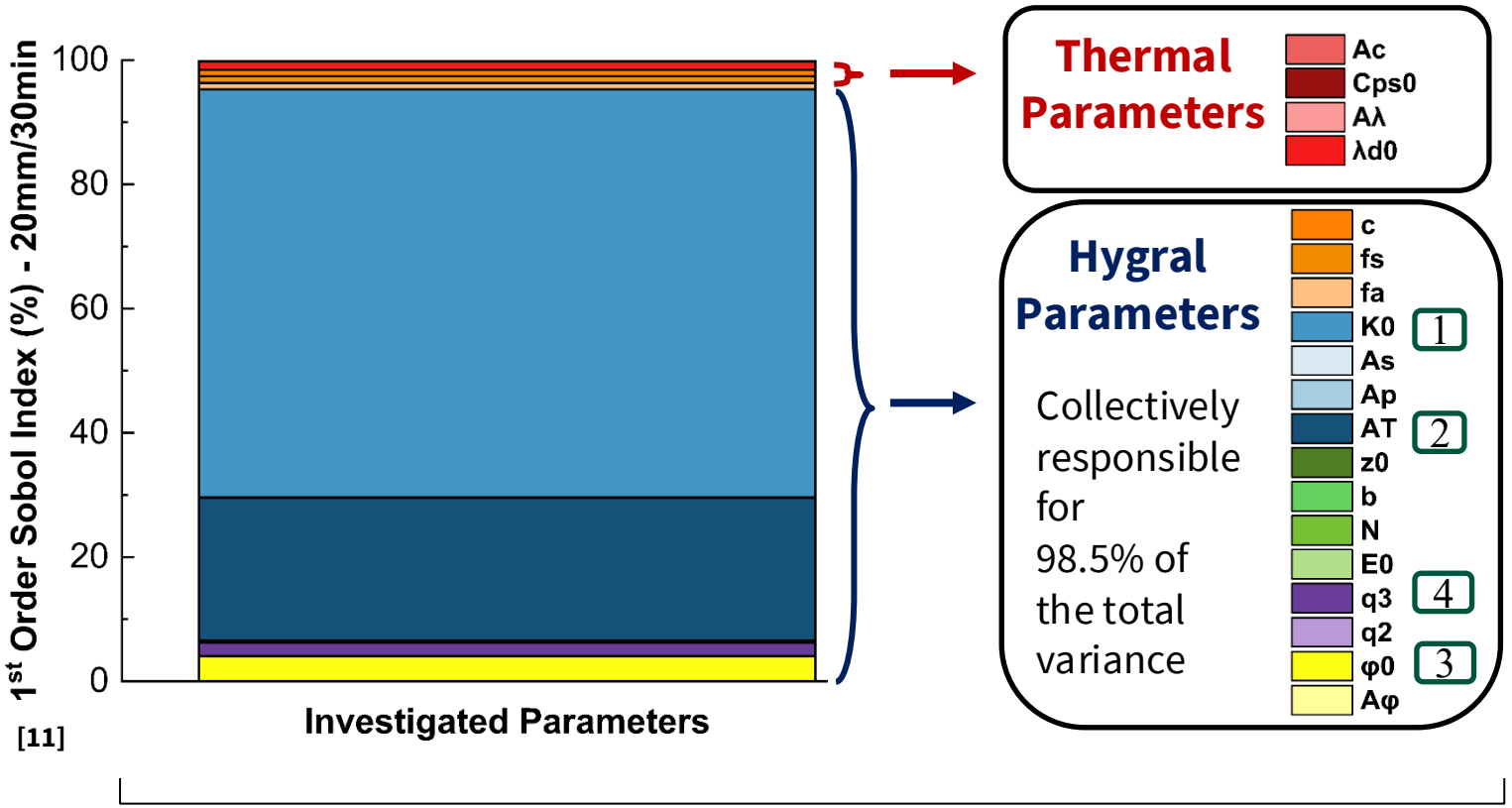
Sorption Isotherms - Liquid Saturation (Pesavento, 2000) :

$$S_l = \left(\left(\frac{\boldsymbol{E} p_c}{a} \right)^{\frac{b}{b-1}} + 1 \right)^{-\frac{1}{b}}$$

Sorption isotherm curve

$$E = E(q1, q2, q3)$$

Sensitivity Index[1] for Investigated Model Parameters

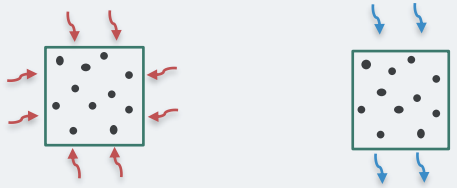


Focus characterization efforts

1. Apostolopoulos, P., Guadagnini, M., Dal Pont, S., Baroth, J., & Torelli, G. (2025). Stochastic finite element analysis of a multiphysics model for heated concrete. Coupled Problems.

Predictive modelling

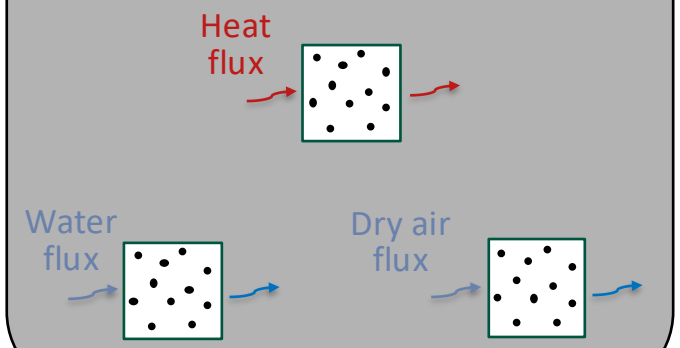
Material Characterization



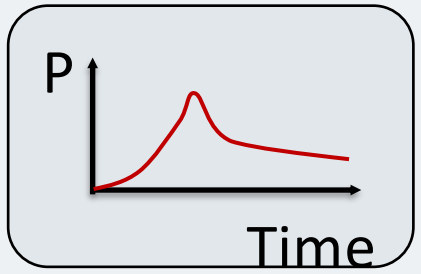
Material Parameters

$\varphi_0,\ K_0,\ C_{ps_0},\ \lambda_d$

Model

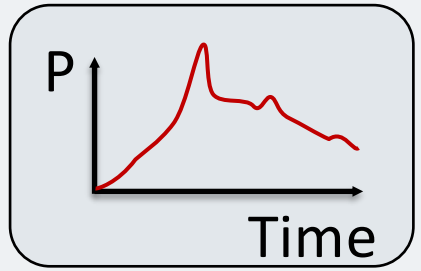


Predicted Pore Pressure



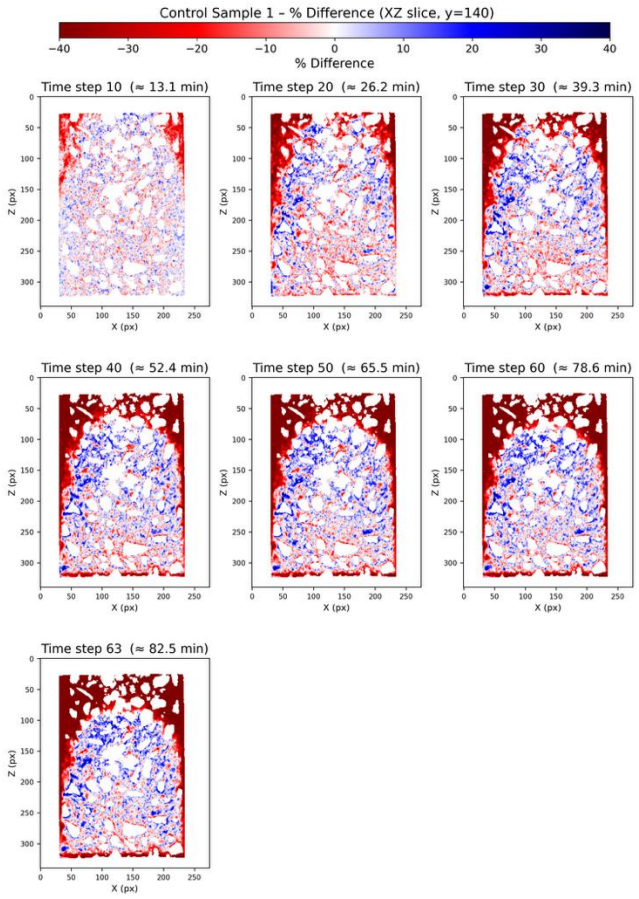
Validation process

Measured Pore Pressure

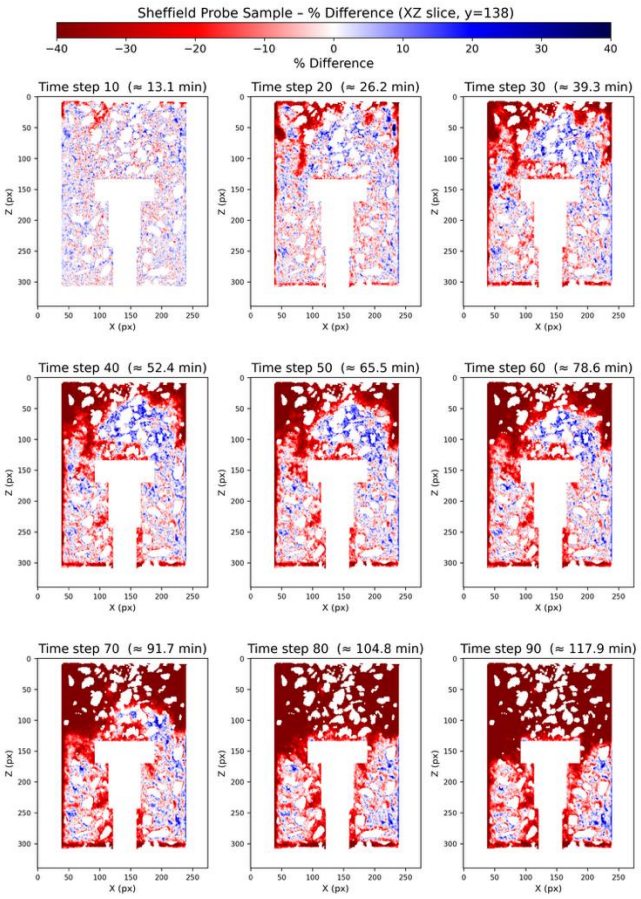


Neutron Tomography

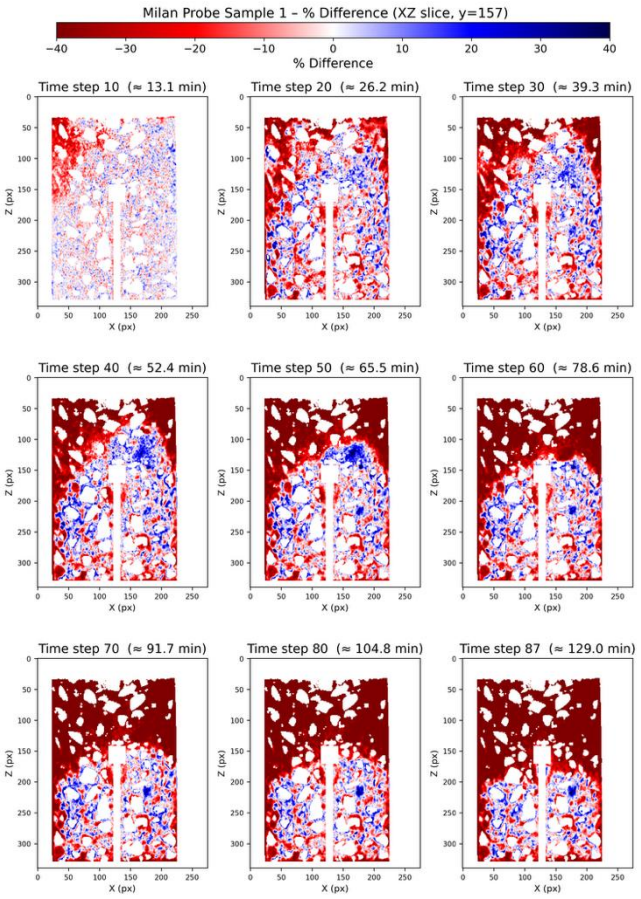
No sensor



Sheffield sensor



Milan sensor

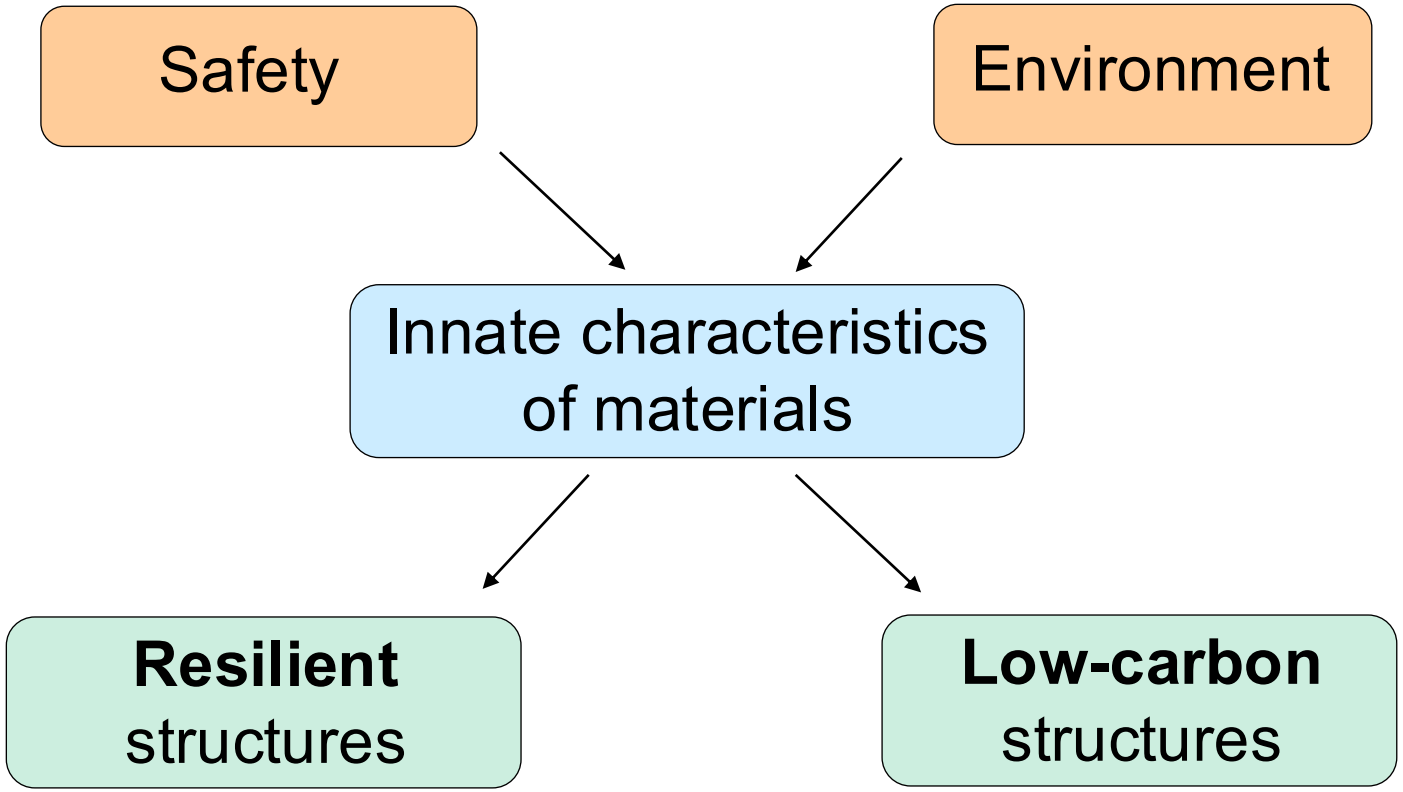


Concluding remarks

- **Parameters K_0 and A_T (permeability law) and φ_0 (porosity law) and q_3 (sorption isotherm)** are the most influential model parameters
- **The rest of the investigated hygral and thermal parameters** have a limited effect on the development of pore pressures
- Future efforts should focus on:
    - Parameter interactions
    - Neutron tomography measurements

Key takeaways
&
Future opportunities

Physics based Multiphysics models



Numerical modelling of concrete at high temperature

Physics-based models

Advanced experiments

Robust materials models

Nuclear Structures



Impact: Safety & Security

Structures in fire

Nuclear Engineering



Material knowledge transfer

Structures in fire



Performance-based design

Impact: Safety & Security

Concrete in Fire: Thermo-Hygro-Mechanical Coupling, Pore Pressure Build-Up, and Material Degradation

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