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The Economics, Performance, and Sustainability of Internally Cured Concrete, Part 2

ACI Fall 2012 Convention
October 21 – 24, Toronto, ON

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EMPA
Materials Science & Technology

Modeling of Internal Curing with SAP at Meso- and Macro-Level

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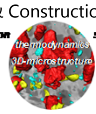
Dariusz Gawin, Lodz University of Technology, Poland

Concrete & Construction Chemistry
hydration sustainability



ACI Fall 2012 Convention, Toronto, October 23

Outline

- Motivation
- Autogenous shrinkage
  - Modeling of phenomena at early age
- Internal curing
  - Modeling internal curing at meso-level
  - Modeling internal curing at macro-level
- Summary

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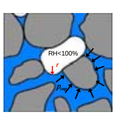
Motivation

Shrinkage and cracking problem

Mechanism Measuring technique

Solution



- *ASTM C1698-09*
- *Loser, Münch, Lura, CCR (2010)*
- *Lura, Jensen, van Breugel CCR (2003)*
- *Jensen & Hansen CCR (2001, 2002)*

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Internal curing with SAP – important questions

Motivation

- When is the water released from the SAP?
- Is the whole volume cured uniformly?
- How far does the internal curing water have to travel?
- How far can internal curing water travel?
- What is the preferred size of the SAP?

• ***Lura, Wyrzykowski et al.*** *Kinetics of water migration in cement-based systems containing super absorbent polymers, RILEM State of the Art Report , 2012*

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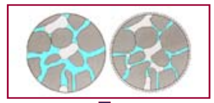
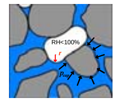
Chemical shrinkage



Self-desiccation



Autogenous shrinkage

▪ ***Lura, Jensen, van Breugel**, CCR **(2003)***
▪ ***Lura & Jensen**, **(2005, 2007)***

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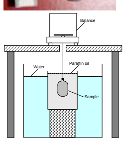
Autogenous deformation

Internal RH

Volumetric measurement



Linear measurement

Water activity (Rotronic)

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- 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

▪ ***Gawin, Pesavento, Schrefler**, IJNME **(2006)***
▪ ***Gawin, Wyrzykowski, Pesavento**, JBP **(2008)***

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- **Macroscopic governing equations**

✓ **The dry air + skeleton mass conservation**

✓ **The water species + skeleton mass conservation**

✓ **The multiphase medium enthalpy balance**

✓ **The multiphase medium momentum balance (mechanical equilibrium)**

✓ **Evolution equation for hydration**

▪ ***Gawin, Pesavento, Schrefler**, IJNME **(2006)***
▪ ***Gawin, Wyrzykowski, Pesavento**, JBP **(2008)***

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- **State variables**
  - gas pressure, p^g
  - capillary pressure, p^c
  - temperature, T
  - displacement vector, $\mathbf{u}$
- **Evolution variable**
  - hydration degree, α_{hydr}

Scheme of the early-age processes description
(hygral and mechanical phenomena)

Hydration evolution
(Ulm & Coussy, 1996)

$$\frac{\partial m_{hydr}}{\partial t} = \frac{\partial \alpha_{hydr}}{\partial t} w_n$$

↓

Water species conservation equation

↓ **Drop of saturation, Increase of capillary pressure**

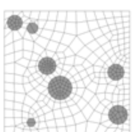
Effective stress principle

↓ **Increase of effective stress**

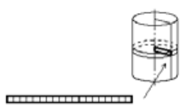
Mechanical equilibrium equation

- **Description of the material behavior at different scale levels**

Meso-level (~mm)



Macro level (~cm-m)



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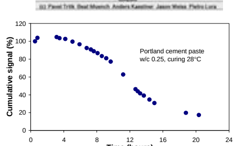
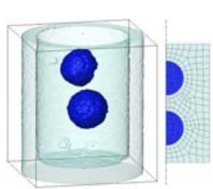
- Meso level simulations



- **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*

- Water and solid skeleton mass conservation

Accumulation terms

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

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

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

Flux terms

Source terms

Modelling internal curing at the meso-level
Mathematical model

- Water and solid skeleton mass conservation-***meso level***
  - autogenous conditions

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

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

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

$$n\rho^{w}\frac{\partial S_w}{\partial p^c}\frac{\partial p^c}{\partial t}=\frac{\rho^{w}}{\rho^{s}}S_w\dot{m}_{hydr}-\dot{m}_{hydr}-div\left[\rho^{w}\frac{kIk^{rw}}{\mu^{w}}\left(-gradp^{g}+gradp^{c}\right)\right]$$

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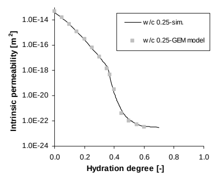
Modelling internal curing at the meso-level

- Simulations at the meso-level
  - characteristics of the components of REV



Permeability evolution in the paste

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

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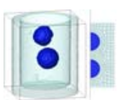
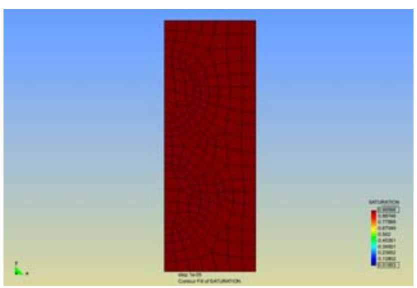
Modelling internal curing at the meso-level

- 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)***

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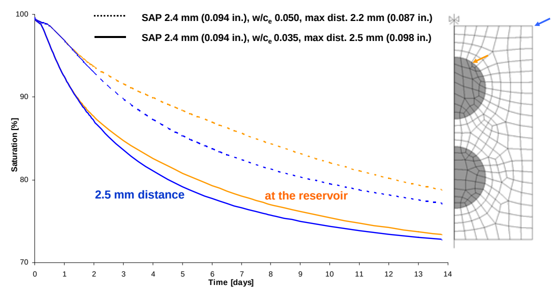
Modelling internal curing at the meso-level

- Saturation evolution in time-cement paste



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

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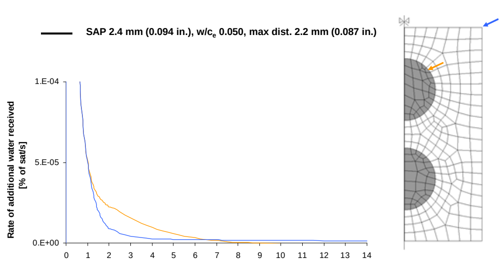
Modelling internal curing at the meso-level

- Saturation evolution in time-cement paste



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

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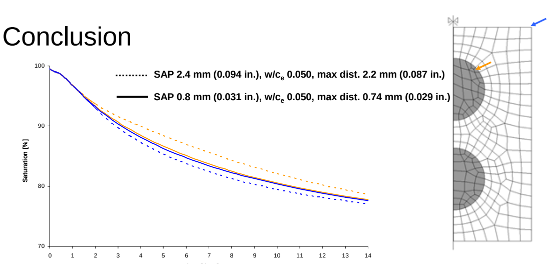
Conclusion



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

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

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- Additional water source term

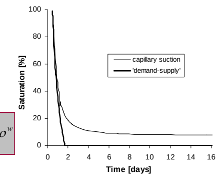
$$n\left(\rho^{w}-\rho^{gw}\right)\frac{\partial S_{w}}{\partial p^{c}}\frac{\partial p^{c}}{\partial t}=\frac{\rho^{gw}}{\rho^{s}}\left(1-S_{w}\right)\dot{m}_{hydr}+\frac{\rho^{w}}{\rho^{s}}S_{w}\dot{m}_{hydr}-\dot{m}_{hydr}+\dot{m}_{IC}$$

Capillary suction

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

Demand-supply

$$\left(1-\frac{\rho^{w}}{\rho^{s}}\right)m_{hydr\infty}\left(\Gamma_{hydr}-\Gamma_{hydr0}\right)\leq\frac{\eta}{1-\eta}\rho^{w}$$



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

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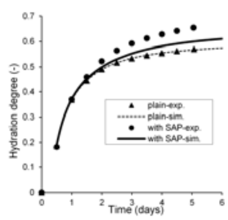
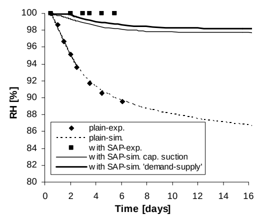
- Simulation results – w/c 0.3 mortar with SAP





Mortars
w/c 0.3 + 0.04

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

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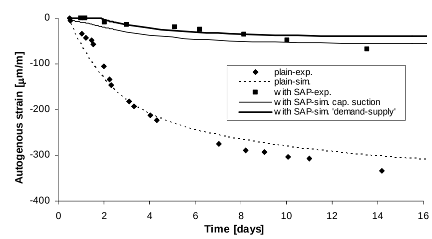

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- At the meso-level the transport of water from SAP is explicitly analyzed
  - the whole volume of material is practically **uniformly and instantaneously** provided with curing water during the first day of hydration
- At the macro-level the additional source term is introduced
  - internal curing may be also analyzed directly at the macro-level
  - two source terms describing internal curing are proposed , i.e., capillary suction mechanism and demand-supply mechanism
  - behaviour of concrete with SAP can be predicted based explicitly on the assumption of additional mositure source

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Thank you !
Concrete & Construction Chemistry
hydration
sustainability
thermodynamics
3D-microstructure
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