CMS Workshop

The workshop on „Cracking of massive concrete structures”, held on 17 March 2015 in Cachan, France, was organised by École normale supérieure de Cachan (ENS-Cachan), supported by Ecole Française du Béton. It was dedicated to the problems of early-age cracking in massive concrete structures.

The aim of the workshop was to establish an international forum of experts and promote discussion as well as exchange of knowledge in the domain of early-age behaviour of concrete structures.

Hereby we present the proceedings of the CMS Workshop.
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Case studies of massive concrete constructions: hydroelectric and nuclear power plants

Eduardo M. R. Fairbairn

1COPPE/UFRJ – The Post-Graduate Institute of the Federal University of Rio de Janeiro
Methodologies

Thermo-chemo-mechanical model
Chemo-mechanical coupling

\[ d\sigma = C(\xi):(d\varepsilon - d\varepsilon^p - d\varepsilon^f - d\varepsilon^v - \alpha(\xi)IdT - \beta(\xi)Id\xi) \]

**\( \sigma \) - stress tensor**

**\( C(x) \) - tensor of elastic properties**

**\( \varepsilon \) - total strain tensor**

**\( \varepsilon^p \) - plastic strain tensor**

**\( \varepsilon^f \) - long-term strain tensor**

**\( \varepsilon^v \) - short-term strain tensor**

**\( \alpha(x) \) - coefficient of thermal dilation**

**\( \beta(x) \) - coefficient of autogenous shrinkage**
Thermo-chemical coupling

\[ c_\gamma T = L \dot{\xi} + k \nabla^2 T \]

- \( c \) – specific heat
- \( \gamma \) – density
- \( L \) – latent heat
- \( k \) – thermal conductivity

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

- \( 0 < \xi < 1 \) – hydration degree
- \( \tilde{A} \) – normalized affinity
- \( E_a \) – activation energy
- \( R \) – universal gas constant
- \( T \) – temperature
Methodologies

Thermo-chemo-mechanical experimental facilities
Experimental framework
Materials and Structures Laboratory @ COPPE/UFRJ
CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

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Specific heat

Thermal diffusivity and thermal expansion coefficient

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Creep

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Creep

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Ambient temperature variation of 700°C
UVP device used to determine the percolation threshold $\xi_0$. 

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Methodologies

Data mining techniques
Binary representation of an individual: chromosome

http://www.ewh.ieee.org/

Methodologies

Computational implementation
• Parallel architecture.
• Computer code DAMTHE/COPPE allows the simulation of layered construction.

Cluster 32 dual nodes
DAMTHE/COPPE: Dynamic partitioning of domains for parallel computing of layered construction

High speed-ups
Case study 1 (academics)

Optimization of the construction of a small dam
GIVEN: the geometry of the structure

DETERMINE \( X^T = \{Hc, Fl, Tc, Tl\} \):

- The height of the lifts (\(Hc\))
- The placing frequency (\(Fl\))
- The type of concrete (\(Tc\))
- The placing temperature (\(Tl\))

Minimizing:

- The cost \(C(X) = C(Hc, Fl, Tc, Tl)\)

Avoiding cracking: \(ECr(X) = ECr(Hc, Fl, Tc, Tl) = 0\)
Optimization flowchart

Input variables:
- height of the lifts
- placing frequency
- placing temperature
- type of concrete

Genetic algorithm:
- Cost evaluation
- penalty -> cracking
- Choice of new input variables

FEM:
- Hydration degree temperature
- Thermal strains Autogenous shrinkage
- stresses
- cracking ?

Optimal variables
Normalized cost:

$$\tilde{c}(X) = \frac{c_{\text{comp}}(Tc) + c_{\text{RC}}(Tl) + c_{\text{Op}}(Hc, Fl)}{c_{t,\text{max}}}, \quad \tilde{c}(X) \in [\tilde{c}_{\text{min}}, 1]$$

Objective function:

$$f(X) = \tilde{c}(X)$$

Fitness function:

$$F(X,t) = f(X) + P(X, t_g)$$

Cracking extension:

$$ECr = \frac{\sum_{i=1}^{n_{\text{plast}}} V_{iel}}{\sum_{i=1}^{n_{el}} V_{iel}} \; ; \; ECr \in [0, 1]$$
Penalty:

\[
P(E_{Cr}(X), t_g) = \begin{cases} 
1 - \tilde{c}_{\min} & \text{if } E_{Cr}(X) > E_{Cr_{\text{lim}}}(t_g) \\
E_{Cr}(X) \frac{1 - \tilde{c}_{\min}}{E_{Cr_{\text{lim}}}(t_g)} & \text{if } E_{Cr}(X) \leq E_{Cr_{\text{lim}}}(t_g)
\end{cases}
\]

\[
E_{Cr_{\text{lim}}}(t_g) = \begin{cases} 
E_{Cr_{\text{lim},0}} - t_g \frac{E_{Cr_{\text{lim},0}}}{N_g/2} & \text{if } 0 \leq t \leq N_g/2 \\
0 & \text{if } N_g/2 \leq t_g \leq N_g
\end{cases}
\]
Fitness function
GA flowchart
Small dam

Geometry

FE Mesh

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Concretes from FURNAS database

\[ Hc(m) = \{ 0.50; 0.75; 1.0; 1.25; 1.50; 1.75; 2.00; 2.5 \} \]

\[ Fl(\text{dias}) = \{ 6; 7; 8; \ldots; 20; 21 \} \]

\[ Tc = \{ 1; 2; 3; 4; 5; 6; 7; 8 \} \]

\[ Tl(\degree C) = \{ 10; 11; \ldots; 20; 25 \} \]

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Costs

\[ H_c(m) \in \{ 0.50 ; 0.75 ; 1.0 ; 1.25 ; 1.50 ; 1.75 ; 2.00 ; 2.5 \} \]

\[ Fl(dias) \in \{ 6 ; 7 ; 8 ; \ldots ; 20 ; 21 \} \]
### CASE STUDIES OF MASSIVE CONCRETE CONSTRUCTIONS

#### E. M. R. Fairbairn

**Title:** CMS Workshop “Cracking of massive concrete structures”

**Location:** Cachan, 17 March 2015

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**Diagram:**

- **Temperature (°C) vs. Time (h):**
  - Materials 1 to 8 are represented by different colors.

- **Costs:**

  $T_e \in \{1; 2; 3; 4; 5; 6; 7; 8\}$
Costs

\[ T_l(\degree C) \in \{10; 11; \ldots; 20; 25\} \]
Evolution of the algorithm

- Limite Superior
- Limite Inferior
- Fitness (Indivíduo)
- Fitness Médio
- Fmin

Parameters:
- Geração = 0
- Fmédio = 0.893
- CrL = 3
- Fmínimo = 0.342
- CrLmínimo = 0.371

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Optimal variables: \( \{ H_c = 1.25m, F_l = 6 \text{ days}, T_c = 8, T_l = 19^\circ C \} \)
Optimal variables: \( \{ Hc = 1.25\text{m}, Fl = 6\text{ days}, Tc = 8, Tl = 19^\circ\text{C}\} \)
Case study 2
Tocoma dam Venezuela
Analysis of two construction schemes
Tocoma hydroelectric power plant
Tocoma hydroelectric power plant
Tocoma hydroelectric power plant: power house
Tocoma hydroelectric power plant: power house
Study of two solutions
Study of two solutions
CASE STUDIES OF MASSIVE CONCRETE CONSTRUCTIONS | E. M. R. Fairbairn
Mesh detail
### Montante

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**construction schedule**
**Jusante**

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</tbody>
</table>

**Construction Schedule**

CASE STUDIES OF MASSIVE CONCRETE CONSTRUCTIONS | E. M. R. Fairbairn
Step 47 – 368 days
Step 47 – 368 days
Comparison of the maximum temperatures

Etapas Construtivas

<table>
<thead>
<tr>
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</table>

Uma casa de força
Duas casas de força
Cracking index, \( t = 198 \) days
Cracking index, $t = 375$ days
Cracking index, $t = 550$ days
CASE STUDIES OF MASSIVE CONCRETE CONSTRUCTIONS | E. M. R. Fairbairn

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- Cracking Index
- Frequency
- One power house
- Two power houses

Frequency distribution graph showing cracking index for one power house and two power houses.
Case study 3
Tocoma dam Venezuela
Analysis of a spillway – complete analysis
Tocoma hydroelectric power plant: spillway
Tocoma hydroelectric power plant: spillway
Tocoma hydroelectric power plant: spillway
Tocoma hydroelectric power plant: spillway
Tocoma hydroelectric power plant: spillway
Layered construction: complete analysis, traditional formwork

2,414,823 tetrahedral linear elements
483,119 nodes
3D model:
2,414,823 linear tetrahedral elements
483,119 nodes
CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

3D model: construction scheme
construction schedule

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* Adotado Material 5 = Material 3
\[ t = 021 \text{ days} \]
$t = 0.28\text{ days}$
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$t = 0.35$ days
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Cachan, 17 March 2015

\[ t = 042 \text{ days} \]
CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

$t = 049$ days
t = 063 days
CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

$t = 098$ days
t = 112 days
CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

$t = 119$ days
CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

\[ t = 126 \text{ days} \]
$t = 140$ days
t = 200 days
Cracking index $t = 140$ days
Cracking index $t = 175$ days
Histogram of cracking index

Vertedor

Indice de fissuracao

Frequencia

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

1.6 \cdot 10^{-4}
3.2 \cdot 10^{-4}
4.8 \cdot 10^{-4}
6.4 \cdot 10^{-4}
8 \cdot 10^{-4}
Case study 4
Tocoma dam Venezuela

Determination of the adiabatic temperature rising by inverse analysis
Fitting of adiabatic temperature rising curves

\[ \Delta T^{ad} = \Delta T_{max}^{ad} \frac{t^n}{k^n + t^n} \]

Variables: \( x^T = \{x_1, x_2, x_3\} = \{T^\infty, k, n\} \)

Fitness function:

\[ F(x) = ET(x) \]

\[ ET(\tilde{x}) = \frac{\sum_{p=1}^{np} E_p(\tilde{x})}{np} \]

\[ E_p(\tilde{x}) = \frac{\sum_{i=1}^{n} \left| T_{p, meas}(t_i) - T_{p, comp}(\tilde{x}, t_i) \right|}{nt} \]

Optimization problem:
Find \( x \) that minimizes \( F(x) \)
FEM analysis temperatures measured in the field

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Determination of adiabatic temperature rise curve

Evolution of algorithm

Adiabatic temperature rise curve
Comparison of measured and calculated temperatures, P1

Verification
Construction of P2 with different pace than P1

Forecasting
Comparison of measured and calculated temperatures, P2

Forecasting
Case study 5
Tocoma dam Venezuela
Analysis of post cooling system and sliding formwork
Tocoma – Spillway gate pier
approximately 33 m height
Simplified model of the gate pier:
114,943 nodes
610,931 elements
Materials properties

<table>
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<th>Property</th>
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<td>( k ) (J/(m.s.K))</td>
<td>2,700</td>
</tr>
<tr>
<td>( C_e ) (J/(kg.K))</td>
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<tr>
<td>( E\alpha / R ) (K)</td>
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<tr>
<td>( \gamma ) (kg/m³)</td>
<td>2330</td>
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<tr>
<td>( \alpha ) (K⁻¹)</td>
<td>9,06 · 10⁻⁶</td>
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<tr>
<td>( \xi_0 )</td>
<td>0,15</td>
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</table>

\[ g^{R,1} \]

\[ 0 \leq \xi < \xi_0 \]
\[ 50 \cdot 10^{-6} \cdot \frac{\xi - 0,1}{1 - 0,1} \text{ if } \xi_0 \leq \xi \leq 1 \]

\[ E \] (MPa)

\[ 0 \leq \xi < \xi_0 \]
\[ 33.672 \left( \frac{\xi - \xi_0}{1 - \xi_0} \right) \text{ if } \xi_0 \leq \xi \leq 1 \]

\[ f_c \] (MPa)

\[ 0 \leq \xi < \xi_0 \]
\[ 3,4 \left( \frac{\xi - \xi_0}{1 - \xi_0} \right) \text{ if } \xi_0 \leq \xi \leq 1 \]

\[ v \]

\[ 0 \leq \xi < \xi_0 \]
\[ 0,2 \text{ se } \xi_0 \leq \xi \leq 1 \]

Age & Compressive strength & Tension strength & Young’s modulus
---|---|---|---|
| (days) & \( f_c \) (MPa) & \( f_{ct} \) (MPa) & \( E \) (MPa)
| 3 & 12.1 & 1.9 & 15,200 |
| 7 & 17.6 & 2.3 & 26,900 |
| 28 & 30.1 & 3.1 & 30,700 |
| 90 & 33.9 & 3.4 & 33,700 |

Adiabatic temperature rise

Elevação adiabática da temperatura (°C)

Tempo (dias)
Simplified FEM model
Gate pier: sliding formwork 10cm/hour
Pre-analysis: initial 9.0 m
Placing temperatures: 20°C; 15°C; 10°C
Simplified FEM model

Gate pier: sliding formwork 10 cm/hour

Pre-analysis: initial 9.0 m

Placing temperatures: 20°C; 15°C; 10°C
Cracking index histograms

CASE STUDIES OF MASSIVE CONCRETE CONSTRUCTIONS | E. M. R. Fairbairn
Post-cooling system
Post-cooling system
Case studies

<table>
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<th>Placing temperature (°C)</th>
<th>Post-cooling temperature (°C)</th>
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Principal tensile stresses at control nodes:
PT=10°C; PCT=10°C
Principal tensile stresses at control nodes:
PT=20°C; PCT=20°C
Histograms of cracking indexes
The post-cooling system implemented in Tocoma: 35 days for the construction of the pier instead of 118 days with the traditional formwork.
Case study 5
Tocoma dam Venezuela

Other studies
Sink:
1.007.194 elements
178.660 nodes
Monolith #02
3 initial layers
1,893,713 el.
331,693 nodes
Monolith #03
3,301,767 elements
584,156 nodes
sliding formworks (20 cm/hour)
placing temperature 25°C
Case study 6
Angra III nuclear power plant
Rio de Janeiro, Brazil
Foundation of auxiliary building
Agra III nuclear power plant
Agra III nuclear power plant
Agra III nuclear power plant
Slab foundation $h = 1.80$ m
Slab foundation $h = 1.80$ m
Cracking index for placing temperature = 12°C
Cracking index for placing temperature = 11°C
Cracking index for placing temperature = 10°C
Cracking index for placing temperature = 12°C in 2 layers, 3 days delay between layers
Case study 7
Angra III nuclear power plant
Rio de Janeiro, Brazil

Reactor dome
Mesh: 2,233,880 elements e 404,129 nodes
Construction with 2 layers

Mesh - detail
Cracking index for placing temperature = 10°C
Cracking index: 16 days

Cracking index for placing temperature = 12°C, 2 layers
Agra III power plant: reactor dome
Agra III power plant: reactor dome
Case study 8
Angra III nuclear power plant
Rio de Janeiro, Brazil

Foundations of auxiliary building
Plan of building UPC
Executive plan for concrete pouring
Executive plan for concrete pouring
Logistics for construction of the several volumes
Logistics for the construction of the several volumes
Cracking index
Case study 9
Angra III nuclear power plant
Rio de Janeiro, Brazil

Other studies
CMS Workshop “Cracking of massive concrete structures”
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Angra III
References


Degree of restraint concept for analysis of early-age stresses in concrete walls

Agnieszka Knoppik-Wróbel¹,*
¹Silesian University of Technology, Department of Structural Engineering, Gliwice, Poland

*Agnieszka Knoppik-Wróbel is a scholar under the project „DoktoRIS” co-financed by EU – European Social Fund.
Introduction

early-age stresses in concrete walls
Concrete structures subjected to early-age cracking

- **massive internally-restrained**
  - thick slabs,
  - blocks,
  - gravity dams

- **medium-thick externally-restrained**
  - tank walls,
  - nuclear containment walls,
  - bridge abutments,
  - retaining walls
Early-age stresses in walls

self-induced and restraint

origin of cracking

self-induced stresses

restraint stresses

\[ \sigma_{xx} \]

\[ t_s \quad t_{0,\text{int}} \quad t_{0,\text{sur}} \quad t \]

\[ \text{interior} \quad \text{surface} \]

\[ \sigma_{xx} \quad \sigma_{\text{max},\text{int}} \quad \sigma_{\text{max},\text{sur}} \]

\[ t_s \quad t_t_{0,\text{int}} \quad t_{t_{0,\text{sur}}} \quad t_{\text{max},\text{int}} \quad t_{\text{max},\text{sur}} \quad t \]

\[ \sigma_{\text{cr}} \]

\[ \sigma_{\text{max}} \quad \sigma_{\text{tensile}} \quad \sigma_{\text{thermal-shrinkage}} \]

\[ t_s \quad t_{\text{cr}} \quad t \]
Early-age stresses in walls

Dominating influence of the thermal restraint stresses.
Cracking pattern vs. mode of restraint

base- and end-restraint

mixed modes
Theoretical background

degree of restraint concept
Compensation Plane Method

**Total Stress**

- Due to internal restraint
- Due to external restraint

*JSCE standard, 2011*
CPM – self-induced stress

Stress due to internal restraint – unbalanced strain due to gradients of temperature and humidity

\[ \sigma_{int} = E_{c, eff} (\varepsilon_0 - \varepsilon_{comp}) \]

\[ \varepsilon_0 = \varepsilon_T + \varepsilon_{sh} \]

\[ E_{c, eff} = \frac{E_c}{1 + \varphi} \]
CPM – restraint stress

Stress due to external restraint – translational and rotational

\[ \sigma_{ext} = \frac{N}{A_c} + \frac{M}{I_c} (y - y_{cen}) \]

\[ N = R_N \cdot E_c \cdot A_c \cdot \bar{\varepsilon} \]
\[ M = R_M \cdot E_c \cdot I_c \cdot \bar{\phi} \]
Degree of restraint

Models using the concept of the restraint factor as representation of the degree of restrain:

1. standards
   • Japan: JSCE Guidelines for Concrete, JCI Guidelines;
   • USA: ACI Report 207.2;
   • Europe: Eurocode 2 Part 3 + CIRIA C660;

2. other methods
   • Sweden: Luleå University of Technology [Nilsson, 2003];
   • Poland: Cracow University of Technology [Flaga, 1990].
Restraint coefficient
[Nilsson, 2003]

\[ \delta_{\text{res}} = \delta_{\text{res}}(L/H) \]
\[ \delta_{\text{slip}} = \delta_{\text{slip}}(L/H) \]
\[ \gamma^t_R = \gamma^t_R \left( \frac{L \ A_F E_F}{H \ A_c E_c} \right) \]
\[ \gamma^{\gamma y}_R = \gamma^{\gamma y}_R (H_c, H_F) \]
\[ \gamma^{\gamma z}_R = \gamma^{\gamma z}_R (B_c, B_F) \]

\[ \sigma = \gamma_R \cdot \sigma_{\text{fix}} \]
\[ \gamma_R(y) = \delta_{\text{slip}} \cdot \left[ \delta_{\text{res}}(y) - \left( \gamma^t_R(y) + \gamma^{\gamma y}_R(y) + \gamma^{\gamma z}_R(y) \right) \right] \]

resilience factor, \( \delta_{\text{res}} \)
slip factor, \( \delta_{\text{slip}} \)
Strategy for analysis

modelling
Aim of the study

To **analyse** the character and magnitude of early-age stresses occurring in concrete walls due to thermal–shrinkage effects and to **investigate the influence of restraint conditions** including the soil–structure interaction.
Degree of restraint in numerical analysis

Luleå Technical University (LTU) Sweden

Anders Hösthagen Majid Al-Gburi

Local Restraint Method (LRM) Equivalent Restraint Method (ERM)

Analysis of cross-section
Self-induced stress, $\sigma_{fix}$

LRM or ERM (general-purpose 3D FEM software)

Total stress $\sigma = \gamma_R \cdot \sigma_{fix}$

Degree of restraint in early-age concrete walls

$\gamma_R$
Numerical model

Strategy: reverse of LRM/ERM

Thermal–moisture analysis

- **concrete**: coupled thermal–moisture equations [Klemczak, 2011]
- **soil**: partially coupled equations; moisture diffusion dependent on temperature [Clapp and Hornberger, 1978]
- **initial conditions**: initial temperature and moisture content
- **boundary conditions**: 3rd type
- **concrete source function** in thermal equation and **sink function** in humidity equation – hydration heat rate
  - $q = \dot{Q}, Q(t)$ - approximation with exponential function,
  - based on cement composition [Schindler and Folliard, 2005]
Stress analysis – concrete

- **viscoelasto-viscoplastic** material model with consistent conception [Klemczak, 2014]
- yield surface and boundary surface are rate-dependent
- modified 3-parameter Willam–Warnke (MWW3) failure criterion [Majewski, 2004; Klemczak, 2007]
- **creep** function acc. to Model Code 1990 [Guénot et al., 1994]
- **maturity development** expressed with time development of mechanical properties [Model Code 2010]
- **equivalent age of concrete**
Stress analysis – soil

- **elasto–plastic** material model [Majewski, 1995]
- Drucker–Prager failure criterion [Majewski, 1995]
- **Mechanical parameters** acc. to Duncan and Chang [Duncan and Chang, 1970] modified by Majewski [Majewski, 1995]
- Soil–structure interaction by application of contact elements [Majewski, 1995]
Influence of restraint conditions

external restraint, geometry and dimensions, support conditions, soil–structure interaction
Influence of external restraint

Verification and comparison on the benchmark tunnel wall in Sweden [Hösthagen, 2014]
Stresses in different wall segments

1st lift
heating

cooling

2nd lift
heating

cooling
Cracking in different wall segments

1st lift

2nd lift

real cracking image
Influence of walls dimensions

- 12 walls with $L/H$ from 1.4 to 10
- several walls with equal $L/H$ but different $L$ and $H$

- $A_C = A_F$ and $I_C = I_F$

- $H_C = H_F$ and $B_C = B_F$
Influence of walls dimensions

Numerical calculations

Analytic approach

Conclusion: results comply to some extent only. In walls with equal $L/H$ ratio the degree of restraint is not the same.
Walls with equal lengths

„Normalised” restraint factor

\[ \gamma'_R = \frac{\gamma_R}{M_1} \]

Influence of walls height

Conclusion: with the increasing height of the wall the magnitude of the restraint decreases. This relationship becomes more pronounced as the length of the wall increases.
Walls with equal $L/H$ ratios

„Normalised” restraint factor

\[ \gamma_R = \frac{\gamma_R}{M_2} \]

Influence of walls area

Conclusion: with the increasing area of the wall (increasing length, increasing height) the magnitude of the restraint decreases. The influence of the walls area increases with the increasing $L/H$ ratio.
Influence of support conditions

Two walls:
- **short** \((L/H = 1.4)\)
- **long** \((L/H = 7)\)

Two types of soil:
- **soft**
- **hard**

\[ K_{\text{hard}} \gg K_{\text{soft}} \]
\[ G_{\text{hard}} \gg G_{\text{soft}} \]

\(~ \times 100\)
Influence of support conditions

**Conclusion:** effect of support conditions visible in long wall; effect of soil: occurrence of rotation + translational restraint
Influence of support conditions

Total rotational restraint

Hard soil

Soft soil

Stress redistribution due to cracking

Little rotation → little effect on $\gamma^{ry}_{R}$

Small length → little effect on $\gamma^{t}_{R}$

Large rotation → large effect on $\gamma^{ry}_{R}$

Great length → huge effect on $\gamma^{t}_{R}$
Conclusions

1. In determination of the degree of restraint not only the $L/H$ ratio but also the individual dimensions of the wall ($L$ and $H$) must be taken into account – scale effect.

2. Real support conditions must be provided in analysis of walls which means introduction of the soil block to simulate:
   - the founding soil with its real properties (stiffness)
   - the possibility of loss of contact between the foundation and the soil as a result of ends lifting due to rotation of the structure.
References
Early-age stresses in concrete structures — modelling and analysis

References

Degree of restraint

12. American Concrete Institute; ACI 207.2R-07: Report on thermal and volume change effects on cracking of mass concrete, 2007
14. Japanese Concrete Institute; JCI Guidelines for control of cracking of mass concrete, 2008
Internal visco-elastic modulus for stress analysis of early-age concrete

E.A.B. Koenders¹, W. Hansen²
¹Technical University of Darmstadt, ²University of Michigan
Introduction

Photo courtesy of O.M. Jensen
Introduction

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Photo EAB Koenders, San Francisco Airport, 2014
Introduction

Classical approach for early age stresses

\[
\Delta \sigma(t) = \Delta \left[ \varepsilon_T(\alpha) + \varepsilon_{cs}(\alpha) + \varepsilon_{as}(\alpha) \right] \cdot E(t)(\alpha) \cdot R
\]

\[
\Delta \sigma(t, \tau) = \Delta \sigma(t) \cdot \psi(t, \tau)
\]

\[
\sigma(t) = \sum_{i=0}^{j} \Delta \sigma(t, \tau)
\]
Introduction

Relaxation factor
Introduction

Classical approach for early age stresses

Breugel (1985)

\[ \psi(\tau_i, t, \alpha_{\tau,i}, \alpha_t) = \exp\left(-\frac{\alpha_h(t)}{\alpha_h(\tau_i)} - 1 + 1.34 \cdot \omega^{1.65} \cdot \tau_i^{-d} \cdot (t - \tau_i)^n \cdot \frac{\alpha_h(t)}{\alpha_h(\tau_i)} \right) \]

Other approach (Schlangen (2006):)

\[ \psi(t) = E_{\text{factor}}(t) \cdot t_{\text{factor}}(t) \]

\[ E_{\text{factor}}(t_i) = \frac{E_{t_i}}{E_{t=168h}} \]

\[ t_{\text{factor}}(t_i) = -0.05 \cdot \ln(t_i - t_{i-1}) + 1 \]

\[ \tau \quad = \text{time when the stress increases} \]
\[ \text{wcr} \quad = \text{w/c-ratio} \]
\[ \alpha \quad = \text{degree of hydration} \]
\[ d \quad = \text{constant depending on the hydration rate of cement,} \]
\[ \text{slow cement: } d = 0.3 \]
\[ n \quad = \text{constant factor} = 0.3 \]
Introduction

Concept of Early-Age Self-Induced Tensile Stresses due to Restrained Deformation Assuming Stress Relaxation

Introduction

TSTM Testing Principle

To measure early age stresses and deformations

Lokhorst
TU Delft
1995

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Introduction

TSTM Testing Principle

Early age stress measurements

Lokhorst
TU Delft
1995
Introduction

TSTM Testing Principle

Early age deformation measurements
Introduction

TSTM Testing Principle

Temperature

TSTM specimen

Temperature

Dummy specimen

Temperature

1 day
3 days
7 days
28 days

Compressive strength

Lokhorst
TU Delft
1995
Hydration of cementitious materials in concrete is affecting its autogenous shrinkage and the associated viscoelastic stress development.

**Internal and External Drying**

**Autogenous shrinkage**

- Uniform moisture gradient due to self desiccation
- Free autogenous shrinkage
- Stress status if autogenous shrinkage is restrained

**Drying shrinkage**

- Differential moisture gradient due to external drying
- Free drying shrinkage
- Stress status if drying shrinkage is restrained
Introduction

Autogenous stress versus deformation
Free and Restrained Autogenous Shrinkage

Sealed curing by double layer plastic

Movable end plate with LVDT attachment

Friction control by rubber pad lining
Free and Restrained Autogenous Shrinkage

0.35 w/b ratio paste

With rebar  Without rebar

0.35 w/b ratio mortar (40% sand)

Free shrinkage

Tensile strain region

Restrained shrinkage

Rebar in compression

Concrete in tension

Free shrinkage $\varepsilon_c(t)$

Rebar restrained shrinkage $\varepsilon_r(t)$

Structural analysis $\varepsilon_c(t) - \varepsilon_r(t)$
Free and Restrained Autogenous Shrinkage

Bond-slip relationship

 INTERNAL VISCO-ELASTIC MODULUS OF EARLY-AGE CONCRETE | E.A.B. Koenders and W. Hansen
Free and Restrained Autogenous Shrinkage

\[ E_v = E_s n_s / \left( \frac{\varepsilon_{sh}(t)}{\varepsilon_s(t)} - 1 \right) \]

Where:
- \( \varepsilon_{sh}(t) \) = free shrinkage of plain mix,
- \( \varepsilon_s(t) \) = steel deformation in RC mix,
- \( A_c \) = area of concrete,
- \( A_s \) = area of steel,
- \( n_s \) = steel ratio,
- \( E_s \) = steel modulus,
- \( E_v \) = viscoelastic hydration modulus.

0.35 w/b ratio paste

With rebar | Without rebar

0.35 w/b ratio mortar (40% sand)
Hydration Modulus $E_v$ and Young’s Modulus $E_c$

- Low Hydration Modulus due to High Internal Deformation Capacity (Interlayer & Capillary Pores)
- Young’s Modulus controlled by Aggregate Stiffness and High Volume Fraction

![Graph showing relationship between free strain and restrained strain for different concrete mixtures. The graph includes data points for 035-paste, 035-20%agg., 035-40%agg., and 035-60%agg. with a line indicating $E_v = 8,500$ MPa and $E_c = 32,000$ MPa.]
Components for total Tensile Stress Prediction

The Pickett shrinkage model:

\[ \varepsilon_c = \varepsilon_p (1 - V_a)^n \]

- \( V_a \) Agg. content
- \( \varepsilon_c \) Concrete shrinkage
- \( \varepsilon_p \) Paste shrinkage

The Pickett shrinkage model is ideally suited for modeling autogenous shrinkage as it is developed for a uniform paste shrinkage stress within a cross section.
Mechanical Components for Total Tensile Stress Prediction

Static modulus development

- Measured static modulus
- Modeled static modulus

Strength development

- Compressive strength
- CEB-FIP model
- Split tensile strength
- S-curve model

Tensile strength, MPa

Compressive strength, MPa

Age, days

Modulus, MPa

Age, days

191

INTERNAL VISCO-ELASTIC MODULUS OF EARLY-AGE CONCRETE | E.A.B. Koenders and W. Hansen
Early-Age Tensile Stress Prediction Methodology

Tensile stress

\[ \sigma_{\text{tensile}}(t) = \sigma_{\text{thermal}}(t) + \sigma_{\text{shrinkage}}(t) \]

Thermal stress from TSTM

\[ \sigma_{\text{thermal}}(t) = (T_{\text{zero}} - T_c) \times CTE \times E_t \times R_f \]

Shrinkage stress

\[ \sigma_{\text{shrinkage}}(t) = E_v \times \varepsilon_{sh}(t) \times R_f \]

\( R_f \): Restraint factor (0-1)

\( CTE \): Coefficient of thermal expansion

\( E_t \): Elastic tension modulus

\( E_v \): Internal visco-elastic modulus
Early-Age Tensile Stress Prediction Methodology

Stress from autogenous deformation

\[ \sigma_{\text{shrinkage}}(t) = E_v \times \varepsilon_{\text{sh}}(t) \times R_f \]

**Graphs:**
- **Left:** Autogenous deformation [ ‰ ]
  - Experiment
  - HYMOSTRUC
  - Portland cement paste
  - Blaine 420 m²/kg
  - Time [hours]: 0, 100, 200, 300, 400, 500

- **Right:** Autogenous deformation [ ‰ ]
  - Experiment
  - HYMOSTRUC
  - Portland cement paste
  - Blaine 300 m²/kg
  - Time [hours]: 0, 400, 800, 1200, 1600

**Legend:**
- wcr 0.4
- wcr 0.3

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Early-Age Tensile Stress Prediction Methodology

Stress from autogenous

\[ \sigma_{\text{shrinkage}}(t) = E_v \times \varepsilon_{sh}(t) \times R_f \]

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Early-Age Tensile Stress Prediction Methodology

Stress from temperature

\[ \sigma_{\text{thermal}}(t) = (T_{\text{zero}} - T_c) \times CTE \times E_c^t \]

- \( T_{\text{zero}} \): Temperature at zero
- \( T_c \): Temperature at clock time
- \( CTE \): Coefficient of Thermal Expansion
- \( E_c^t \): Elastic modulus at clock time
Probability method for tensile failure (Lokhorst)

1% probability of failure ~ 0.56 stress/strength ratio
Early-Age Tensile Stress Prediction Without Thermal Effects

Shrinkage stress prediction for 28-day autogenous shrinkage (~ 172 x 10^{-6})

28-day shrinkage stress is significant
Important parameters

So: What are now the important parameters?

**Paste:**
- Relative Humidity: RH
- Pore size distribution: $\phi$
- Blaine: [$m^2/kg$]
- w/c ratio

**Concrete:**
- Aggregate ratio
- Reinforcement ratio

---

**Pore structure model**
- Adsorption layer
- Pore pressure / humidity
- Capillary water

**Microstructure**

---

Pore structure in microstructure dependent
Conclusions

• The internal Shrinkage Modulus $E_v$ is obtained from Autogenous Shrinkage Measurements

• Total Stress Analysis of High Performance (low w/c ratio) Cementitious Materials incorporate significant contribution from restrained Autogenous Shrinkage
References


Progress in the consideration of the microstructure effects on the aging behaviour of concrete

Frédéric Grondin¹, Ahmed Loukili¹
¹Institut de Recherche en Génie Civil et Mécanique (GeM), Ecole Centrale de Nantes, France
Introduction
Structures made with cast concrete are submitted to high loads at early ages. Their effects, particularly the creep strains, are significant.

Structures made with reinforced concrete (shrinkage induces creep)

Evolving applied loading

Underground structures (soil pressure effect)

Constant applied loading

How the creep develops in reinforced concrete at early ages?
Restrained shrinkage (6.10m x 0.80m x 0.50m)
RG8b: reference concrete and reinforcement

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Restrained solidification in concrete

At early ages, local stresses occur on reinforcement in reinforced concrete due to shrinkage. This implies creep which can lead to microcracking.
Concrete: a heterogeneous complex material

Concrete is formed by a chemical process between cement and water and aggregates are used for the consolidation. Many chemical reactions occur and give a lot of different phases with different properties.

How to model its mechanical behaviour?

Standards
Mechanical behaviour law

Poro-mechanical
behaviour law

Chemo-poro-mechanical
behaviour law
What is the interest in the development of multiscale models for concrete?

For standard and macroscopic models, laboratory experiments are expected to characterize material properties and some coefficients which are used to define micromechanisms (interactions between components)

In case of new materials or complex conditions, laboratory investigations are long and difficult to analyze without a good comprehension of the micromechanisms.

Experiments need to be assisted by micromechanical models: multi-scale methods are expected!
Goal

- Study of the coupling between creep and damage at early ages (a)
- Understand the micro-mechanisms which induce creep (b)

a) Experiments
   - Development of an original device for flexural creep tests

b) Modelling
   - Development of a numerical multiscale model
New experimental device for creep tests
Creep of \textit{mature} concrete has been studied by many authors (Bazant et al., 88; Sanahuja et al., 09; Omar, 04; Reviron, 09; Saliba, 2012).

The creep study of young concrete has been studied by compressive and tensile tests (Briffaut, 10; Jiang, 14...)

Lack of flexural creep tests on concrete
Why a new creep device?

➢ Device developed at GeM Institute

Limitations of this device?

😊 Failure tests (stress relaxation + can not measure the crack opening)

😊 Only one control mode (by force load)
Presentation of the new device

**Advantages**

- Failure tests (no stress relaxation + measurement of the crack opening)
- Two control modes (by CMOD and by force load)
- Creep tests on cracked concrete beam
The bearing load gives much larger displacements than those obtained by a constant load.

Complex creep loads
Failure behaviour after creep

The bearing load most contributes to the loss of rigidity with a small decrease in the flexural strength.

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Failure behaviour after creep on pre-damaged beams

Loss of rigidity and significant decrease in the flexural strength for the pre-damaged beams
In brief

Developpement of a new device to perform flexural tests:

- Of creep at early ages
- Of failure after a creep period without stress relaxation
- Of creep on pre-damaged beams

Characterization of the delayed behaviour

- Amplitude of the basic creep is important in the case of a bearing load

Characterization of the mechanical behaviour after creep

- **Undamaged beams under a constant load**
  - Negligible effect of creep

- **Undamaged beams under a bearing load**
  - Loss of rigidity with a low decrease of the flexural strength

- **Pre-damaged beams under a constant load**
  - Loss of rigidity with an important decrease of the flexural strength
Does microcracking occur at low loading?

A portion of the velocity reduction remains within the concrete body and accumulates after each loading test.
Modelling of early-age creep
What is the interest in the development of multi-scales creep models for concrete?

At the mesoscopic scale, we make some assumptions on the visco-elasticity of the matrix but we do not consider explicitly the viscous behaviour of C-S-H as recommended by many authors.

The influence of C-S-H on creep of concrete is more important at early ages. Because the volume fraction of C-S-H increases significantly and its viscous behaviour plays an important role. It allows limiting the micro-cracking due to early-age shrinkage. But it leads to a redistribution of local stresses and can cause new micro-cracking.
Theory: focus on the secondary creep

The main theory adopted to explain the secondary creep is the sliding of the calcium silicate hydrates (C-S-H).

Bazant and Prasannan (1988) have introduced the solidification theory to explain the creep of concrete: The aging is treated as a consequence of volume growth of the load-bearing solidified matter (hydrated cement) whose properties are nonaging and are described by a Kelvin chain with age-independent moduli and viscosities.
Concrete Mortar Cement paste

Matrix: CSH+ pores

**Presentation of the multiscale model**

**Step 1:** Inverse approach to determine the viscoelastic parameters of the matrix at the lowest scale (CSH in this study) without evolution of the volume fractions.

**Step 2:** Study of the age influence and the evolution of the porosity on the creep of concrete

**Step 3:** Validation of the model by experiments
Effect of the pores quantity on the coefficients of the cement paste matrix (Ricaud et al., 2009):

For each Kelvin-Voigt chain

$$ k_{bc}^i = \frac{4. \frac{\xi_i}{\tau_i}}{3.A(f_p)} = \frac{4.k_{int}^i}{3.A(f_p)} $$

Characteristic coeff. defined for an unvolving material

Porosity
Chemical relations

Residual clinkers

\[ V_X(t) = V_{c0} f_X (1 - \xi_X(t)) \]

Residual water

\[ V_E(t) = V_{E0} - \sum V_X^E \xi_X(t) \]

with

\[ V_X^E = V_{c0} \frac{n_{PC} f_X}{n_X \rho_E} \frac{M_X}{M_E} \]

Hydrates

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

with

\[ C_i^j = V_{c0} \frac{n_i^s \rho_{PC} f_j}{n_j^p \rho_i} \frac{M_j}{M_i} \]

Gypsum

\[ V_{gyp}(t) = V_{c0} f_{gyp} (1 - \beta \cdot (3 \xi_{C3A}(t) - 3 \xi_{C4AF}(t))) \]

Ettringite

\[ V_{ett}(t) = V_{ett}(t_g) (1 - 0.5 \xi_{C3A}(t) - 0.5 \xi_{C4AF}(t)) \]
Concrete scale: choice of the mortar’s parameters

Paste scale: choice of the (CSH+pores) parameters

Mortar scale: choice of the paste parameters

Compliance (µm/m/Mpa)

Time (days)

<table>
<thead>
<tr>
<th></th>
<th>E(GPa)</th>
<th>k¹lp (GPa)</th>
<th>k²lp(GPa)</th>
<th>k³lp(GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mortar</td>
<td>22.4</td>
<td>776.7</td>
<td>472</td>
<td>98.1</td>
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<tr>
<td>Aggregate</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cement paste</td>
<td>18</td>
<td>300</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>Sand grains</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CP matrix</td>
<td>12</td>
<td>150</td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td>CP inclusions</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Inverse approach

The characteristic viscoelastic parameters of the cement paste matrix were derived from previous results by using the analytical formula of Ricaud and Masson (2009):

\[
k_{bc}^i = \frac{4.5^i}{\tau^i} = \frac{4K_{int}^i}{3A(f_p)}
\]

<table>
<thead>
<tr>
<th>(k_{int}^1) (GPa)</th>
<th>(K_{int}^2) (GPa)</th>
<th>(K_{int}^3) (GPa)</th>
<th>Age (h)</th>
<th>fp (%)</th>
<th>(k_{bc}^1) (GPa)</th>
<th>(K_{bc}^2) (GPa)</th>
<th>(K_{bc}^3) (GPa)</th>
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</thead>
<tbody>
<tr>
<td>107</td>
<td>57</td>
<td>46.4</td>
<td>16</td>
<td>58</td>
<td>103</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
<td>142</td>
<td></td>
<td></td>
<td></td>
<td>76</td>
<td>62</td>
</tr>
<tr>
<td>48</td>
<td>48.8</td>
<td>150</td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td>65</td>
</tr>
</tbody>
</table>

**Basic coefficients of the cement paste matrix**
## Homogeneization

<table>
<thead>
<tr>
<th>(CSH+pores)</th>
<th>Age (h)</th>
<th>E(GPa)</th>
<th>$k_{bc}^1$ (GPa)</th>
<th>$k_{bc}^2$ (GPa)</th>
<th>$k_{bc}^3$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16</td>
<td>9.5</td>
<td>103</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>10.5</td>
<td>142</td>
<td>76</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>&gt;48</td>
<td>12</td>
<td>150</td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td>Cement paste</td>
<td>16</td>
<td>13.1</td>
<td>170.4</td>
<td>56.8</td>
<td>51.1</td>
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<td></td>
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<td>95.4</td>
<td>85.9</td>
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<td>&gt;48</td>
<td>16.7</td>
<td>300</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>Mortar</td>
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<td>17</td>
<td>483.9</td>
<td>294.1</td>
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<td>21</td>
<td>745.5</td>
<td>453</td>
<td>94.2</td>
</tr>
<tr>
<td></td>
<td>&gt;48</td>
<td>24</td>
<td>777</td>
<td>472</td>
<td>98</td>
</tr>
</tbody>
</table>
Creep-damage coupling

Non-linear viscoelastic behaviour law: \[ \sigma(y) = C(y, \varepsilon(y)) : (\varepsilon(y) - \varepsilon^{fp}(y)) \]

Damage model linking the total stress to the effective stress [Fichant et al., 99]:

\[ \tilde{\sigma}(y) = C^0(y) : \varepsilon^e(y) \quad \text{and} \quad \sigma(y) = C(y, \varepsilon(y)) : \left( C^0(y)^{-1} : \tilde{\sigma}(y) \right) \]

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

\[ \varepsilon_{eq} = \sqrt{\langle \varepsilon^e \rangle_+ : \langle \varepsilon^e \rangle_+} \]
Simulation of the failure tests

Essai Simulation

24h

Force (kN) - Flèche (µm)

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A little gap is observed between simulation and the measurement for the bearing load.

### Simulation of the creep tests

- **Force**
  - $F$ vs. CMOD
  - $30\% F_{\text{max}}$
  - 30d vs. Time

- **Graph**
  - Depiction of displacement over time with markers for Exp (Palier), Sim (Palier), Sim (Cst), and Exp (Cst)
  - 24h marker:
    - Palier 1
    - Palier 2

### Notes
- Force
- Constant load
- Bearing load

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Future couplings

Consideration of the shrinkage
The micromechanical approach

The local hydro-mechanical problem

\[ \nabla \cdot \sigma = 0 \quad \text{in} \ V \\
\sigma = C_1 : \varepsilon \quad \text{in} \ V_1 \\
\sigma = C_2 : \varepsilon - p_c \delta \quad \text{in} \ V_2 \\
\varepsilon = \frac{1}{2} (\nabla u + \nabla u^t) \\
\left\| \sigma \cdot n \right\| = 0 \quad \text{and} \quad \left\| u \right\| = 0 \quad \text{on} \ \partial V \\
u = E \cdot y \quad \text{on} \ \Gamma_{mi} \]

Changing of the capillary pressure (Coussy et al., 2004)

\[ p_c (S) = M (S^{-1/m} - 1)^{(1-m)} \]

M = 37.55 MPa and m = 0.46 are material constant parameters which define the liquid saturation of the cement paste.
The micromechanical approach

The homogenized strain of the cement paste

\[ dE^{cp} = \frac{1}{k^{\text{hom}}} \left[ \frac{p_c (k^{\text{hom}} - k_s^{\text{hom}})}{k_w - k_s^{\text{hom}}} \right] \]

Calculation of the chemical shrinkage (Mounanga et al., 2004)

\[ \Delta \varepsilon(t) = \Delta \varepsilon_{Gy} M_{Gy} + \Delta \varepsilon_{C3S} M_{C3S}(t) + \Delta \varepsilon_{C2S} M_{C2S}(t) + \Delta \varepsilon_{C3A} M_{C3A}(t) + \Delta \varepsilon_{C4AF} M_{C4AF}(t) + \Delta \varepsilon_{\text{En}} M_{\text{En}}(t) \]
Cracking due to shrinkage

- PVC plates (C)
- Laser sensors (D)
- Water flow (Control of the temperature in the mould)
- Thermocouple (Measure of the temperature in concrete)
- Steel mould (A)
Future couplings

Modelling of ITZ
ITZ properties

Thickness between 20 and 50 µm!

Finite element modelling:

If ITZ is represented the REV dimension to element size ratio is oversize

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

Cement volume fraction in the cement paste (Nadeau, CCR, 2002):

\[
\alpha_c(r) = \begin{cases} 
\bar{\alpha}_c \left[ 1 + a_c \left( \frac{r-r_a-\delta}{\delta} \right)^2 \right] & r_a \leq r \leq r_a + \delta \\
\bar{\alpha}_c & r > r_a + \delta 
\end{cases}
\]

(Scrivener et Pratt, 1996)
Definition of a new interphase
Grondin and Matallah, 2014

Interphase properties = Average (layers of ITZ + a bulk fraction)

Cement volume:

\[ V_c = V_c^{\text{ITZ}} + V_c^{\text{non-ITZ}} = \frac{3c_a \overline{c}_c V}{r_a^3} \int_{r_a}^{r_a+\delta} \left[ 1 + a_c \left( \frac{r-r_a-\delta}{\delta} \right)^2 \right] r^2 dr + \overline{c}_c \left[ V - \frac{4}{3} n_a \pi (r_a + \delta)^3 \right] \]
Modelling of the direct tensile load

Grondin and Matallah, 2014

Note: More the hydration is advanced, more the difference between ITZ and bulk decreases.
References

Characterisation of concrete properties at early ages: Case studies of the University of Minho

Miguel Azenha¹, José Granja¹
¹ISISE, University of Minho, Portugal
Index

• Assessing the thermal dilation of concrete since early ages

• Continuous monitoring of concrete E-modulus (EMM-ARM) in the context of the construction of a bridge

• Other recent works and further ongoing research of interest for TC-CMS
Assessing the thermal dilation of concrete since early ages
Scope / Motivation

- Early ages of concrete -> hydration heat -> stresses;
- Limited knowledge about thermal dilation coefficient (TDC);
- Need for new experimental approaches applied to concrete.

Objectives / Organization

- Development of new method to measure TDC;
- Possibility of measuring TDC since early ages;
- Very short temperature cycles and internal cooling;
- Pilot experiment.
Techniques for measurement of the thermal dilation coefficient (TDC)

Volumetric techniques

Techniques based on the longitudinal length variation of a specimen

Limitations:
✓ Sample size
✓ Material suitability

Only applicable to hardened concrete

TDC not measured at early ages

Loser et. al., 2010

AASHTO-T336, 2011
New method for TDC measurement: requirements and considerations

- Temperature cycles to which the specimen is subjected
  - Short enough to maximize the number of measurements of TDC;
  - With enough amplitude to generate measurable volumetric variations.

- Applicable to concrete specimens
  - 150mm diameter and 300mm length (standard size);
  - Internal pipes to accelerate thermal equilibrium state (12mm);
  - Internal strain monitoring with vibrating wire strain gauge.

- Average temperature of 20°C, avoiding maturity corrections
  - Cycles between ~17.5°C e 22.5°C;
  - 180 minutes of duration for each complete cycle (2 measurements per cycle).
Proposal of a new methodology for TDC measurement
Geometry and study of internal pipes

150mm diameter
300mm length

Pipes for water circulation
Vibrating wire strain gage
Proposal of a new methodology for TDC measurement

Specimen and surrounding bath

Section A-A'

Section B-B'

Water ramification device

Internal pipes

Vibrating wire strain gage

Vibrating wire strain gage

Wooden base

Positioning of specimen within surrounding bath
Proposal of a new methodology for TDC measurement
System for heating/cooling the bath

Refrigeration machine

Serpentine

Thermostatic controller

Elevation pump

Circulation pump
Pilot experiment – General information

- Cycles 17.5°C-22.5°C with 180 min duration;
- Test starts 40 min after casting;
- Concrete composition:

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity (kg) per m³ of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg)</td>
<td>500,0</td>
</tr>
<tr>
<td>Sand (0-4) (kg)</td>
<td>851,6</td>
</tr>
<tr>
<td>Gravel (4-8) (kg)</td>
<td>822,9</td>
</tr>
<tr>
<td>Superplasticizer (kg)</td>
<td>10,0</td>
</tr>
<tr>
<td>Water (kg)</td>
<td>181,6</td>
</tr>
</tbody>
</table>
Pilot experiment – Practical implementation

- Internal pipes
- Thermally insulated hoses
- Water circulation
- Submersible pump
Pilot experiment – Practical implementation
Pilot experiment – main results

---

CHARACTERIZATION OF CONCRETE PROPERTIES AT EARLY AGES | M. Azenha and J. Granja
Pilot experiment – main results

- Evolution of the thermal dilation coefficient

  - Instant of solidarization

  - TDC of the sensor
Conclusions

- Proposal of an innovative methodology for measurement of concrete TDC since early ages;

- Main originality: internal pipes (accelerated equilibrium states);

- Pilot experiment with cycles of 180 min, starting shortly after setting;

- Good performance of strain monitoring;

- Values/evolution of TDC plausible in view of the literature.
Continuous monitoring of concrete E-modulus (EMM-ARM) in the context of the construction of a bridge
EMM-ARM - **E-Modulus Measurement through Ambient Response Method**

- Continuous monitoring of the elastic modulus of cementitious materials from the moment of casting;
- General principles of the technique (Azenha et al., 2009):
  
  **Casting a mould with the material to be tested**

![Cylindrical mould](image)

**Acrylic mould**

**Horizontal rods** **Vertical connectors**
EMM-ARM

- Placing the mould in a simply supported condition and monitoring the accelerations at mid-span;

- Identification of the first resonant frequency of the composite beam at each instant while the curing of the material occurs inside the mould.
EMM-ARM – Frequency Identification

- 5 min accelerograms
- Normalized power spectrum density
- Testing beam
- CPU
- Data Logger
- Welch procedure
- Peaks selection
- 3D Surface
- Repeat every 10 min

- 1st resonance frequency
- Acceleration [g]
- Time [s]
- Power [mg²/Hz]
- Frequency [Hz]
- Time (days)
- Frequency (Hz)
Evaluation of Concrete E-Modulus (Based on Modal ID)

Based on the equations of free motion of a simply supported beam with a concentrated load at mid-span

\[
\phi(x) \quad \text{mid-span} \quad m_p \quad E I, \quad m = \text{constants}
\]

it is possible to relate the 1st resonant frequency of the composite beam \( w \) with its stiffness \( \overline{E I} \) (which is the only unknown in the following equation):

\[
- \frac{1}{2k} \left[ \frac{\overline{E I} a^3 \sin(aL)^2 w^2 m_p + 2 \cosh(aL) k w^2 m_p \sin(aL) + \cosh(aL)^2 w^2 m_p \overline{E I} a^3}{4} 
+ 2 \left( \frac{\overline{E I}}{k} \right)^2 a^6 \sinh(aL) - \frac{\overline{E I}}{k} a^3 \sinh(aL)^2 w^2 m_p + 2 \cos(aL) \left( \frac{\overline{E I}}{k} \right)^2 a^6 \sinh(aL) - 
4 \cos(aL) k \overline{E I} a^3 \cosh(aL) + \cos(aL)^2 w^2 m_p \overline{E I} a^3 + 2 \cos(aL) w^2 m_p \overline{E I} a^3 \cosh(aL) - 
2 \cos(aL) k w^2 m_p \sinh(aL) \right] = 0 \quad \text{with} \quad a = \sqrt{\frac{w^2 m}{E I}}
\]

\[
\overline{E I} = E_a I_a + E_c I_c
\]

Concrete E-modulus is obtained.
Several drawbacks:
• Difficult to cast;
• Not robust;
• Non reusable mould;
• Very sensitive to contaminations of the environmental noise.
EMM-ARM improvements – test setup

- Beam span reduction and new mould material
- Implementation of new beam supports

Similar results were obtained, thus validating span reduction and changes in both mould material (PVC) and supports.
EMM-ARM improvements – test setup

- New reusable mould
- Two halves of a PVC tube
- Aluminium reinforcement rings
- Wooden lids
- Robust test setup

Similar results were obtained, thus validating the reusable mould
EMM-ARM improvements – Modal analysis technique

- Comparison between ambient vibration and forced vibration tests:
  - Excitation applied through custom non contact electromagnetic actuator.

- Allows the reduction of the sensitivity to environmental noises
EMM-ARM in-situ application: validation

Foz do Dão bridge:
• EMM-ARM implementation to support decision making in pre-stress applications
EMM-ARM in-situ application: validation

- Extended experimental campaign:
  - Comparison between several types of EMM-ARM beams (reusable, PVC and acrylic);
  - Comparison with classical cyclic compression tests (CC);

- Good repeatability of the EMM-ARM results
- Excellent coherence between EMM-ARM and CC results
EMM-ARM in-situ application: E vs fcm relationship calibration

- Comparison between results under the same curing conditions:
  - Compressive strength (cubes)
  - E-modulus (EMM-ARM beams)

\[ E_{cm} = A \left( \frac{f_{cm}}{B} \right)^C \]

<table>
<thead>
<tr>
<th>A</th>
<th>1.887</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>8.228E-3</td>
</tr>
<tr>
<td>C</td>
<td>0.353</td>
</tr>
</tbody>
</table>

Fitting to the experimental data

\[ f_{cm} \text{ [MPa]} \]

\[ \text{Equivalent age [days]} \]

<table>
<thead>
<tr>
<th>EMM-ARM</th>
<th>Cubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.887</td>
<td>22</td>
</tr>
<tr>
<td>8.228E-3</td>
<td>10</td>
</tr>
<tr>
<td>0.353</td>
<td>0.3</td>
</tr>
</tbody>
</table>

CHARACTERIZATION OF CONCRETE PROPERTIES AT EARLY AGES | M. Azenha and J. Granja
EMM-ARM in-situ application: *match curing system*

- **Temperature sensor in the real structure**
- **Temperature matched chamber**
- **Temperature control system**
- **Data acquisition system**

**Preliminary test**

<table>
<thead>
<tr>
<th>Temperature (ºC)</th>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.0</td>
</tr>
<tr>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td>30</td>
<td>3.0</td>
</tr>
<tr>
<td>35</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Graph**

- Chamber
- Imposed

---

CHARACTERIZATION OF CONCRETE PROPERTIES AT EARLY AGES | M. Azenha and J. Granja
EMM-ARM in-situ application

Temperature matched chamber
Temperature control system
PC
Data acquisition system
Fan
Heater
EMM-ARM beam 1

Chamber
Real structure
Thermocouple

In-situ concrete piece
Chamber
EMM-ARM specimen

CHARACTERIZATION OF CONCRETE PROPERTIES AT EARLY AGES | M. Azenha and J. Granja
EMM-ARM in-situ application

\[ E_{cm} = A\left(\frac{f_{cm}}{B}\right)^C \]

A \quad 1.887
B \quad 8.228E^{-3}
C \quad 0.353

Excellent coherence

Applicability of EMM-ARM under in-situ conditions successfully confirmed.
Other recent works and further ongoing research of interest for TC-CMS
Other recent works

Application of air cooled pipes for reduction of early age cracking risk in a massive RC wall

Miguel Azenha *, Rodrigo Lameiras, Christoph de Sousa, Joaquim Barros

Other recent works

Early-age behaviour of the concrete surrounding a turbine spiral case: Monitoring and thermo-mechanical modelling

José Conceição\textsuperscript{a}, Rui Faria\textsuperscript{a,*}, Miguel Azenha\textsuperscript{b}, Flávio Mamede\textsuperscript{c}, Flávio Souza\textsuperscript{d}

*Corresponding author. 

Ongoing research

VisCoDyn Project – FCT - EXPL/ECM-EST/1323/2013

The intent of this work is to explore the possibility of using dynamic approaches to continuously assess viscoelastic properties of concrete, with the proposal of a new methodology termed VisCoDyn. This innovative implementation can be achieved through the submission of a concrete specimen (e.g. a beam) to a known dynamic excitation.

Task 1: Equipment acquisition, training and software development
Task 2: Assembly of the experimental setup and testing
Task 3: Experimental program and round-robin testing
Task 4: Analytical and numerical evaluation of creep data
Task 5: Dissemination of results and connection with industry
Ongoing research

**COST TU1404 – Short Term Scientific Mission – UMinho - EPFL**

José Granja, Cyrille Dunant, Miguel Azenha, Arnaud Muller

---

Cement Paste:
- Chemical composition
- w/c ratio
- PSD of the particles
- Reactions

---

EMM-ARM for cement pastes

---

3D Model

Meshing

Hydrated and anhydrated phases:
- Mechanical properties

Back analysis to get the properties

---

Several unknown properties!

---

EMM-ARM

Simulation

---

Characterization of Concrete Properties at Early Ages | M. Azenha and J. Granja

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Acknowledgements

- FCT PhD grant SFRH/BD/80682/2011.
- FCT research project VisCoDyn EXPL/ECM-EST/1323/2013.
- COST Action TU1404 (STSM).
- Andreia Silva and Nuno Carvalho for their assistance in the experimental programs.
Shrinkage induced cracking risk of concrete

*LGC - Civil Engineering Lab – ULB – Brussels - Belgium
**GeM – Centrale Nantes - France
Focus on the influence of the water saturation of aggregates on shrinkage induced cracking risk of concrete

E. Rozière, S. Staquet, R. Cortas, A. Hamami, A. Loukili, M.-P. Delplancke-Ogletree
• Observations

Early-age cracking of concrete (before 24 hours):

**Case 1:** Slabs.
Influence of aggregate type.
Water$_{\text{eff}}$/Cement = 0.5 – 0.6

**Case 2:** Raft slab foundations, walls.
Influence of **aggregate water saturation**, paste volume and $W_{\text{eff}}$/C.
$W_{\text{eff}}$/C = 0.45
• Restrained shrinkage caused cracking

[ACI 224 – 01]
Early-age cracking: experimental approach

Self generated stress under various exposure conditions, and uniaxial tensile strength:
- Sealed (“S”, 20°C),
- Sealed and cooled (“S, 20–10°C”), exposed to air (“ES, 20°C”)
- Exposed to air and cooled (“ES, 20–10°C”).

Hammer et al., Materials & Structures, 2007

Ravina & Shalon, ACI, 1968

Hammer et al., Materials & Structures, 2007
Outline

• Experimental program
  ➢ Measurement of early-age shrinkage
  ➢ Mix design

• Early-age shrinkage
  ➢ Autogenous and plastic shrinkage
  ➢ Porosity
  ➢ Strength

• Cracking
  ➢ Experimental approach
  ➢ Effect of water saturation of aggregates
Early-age shrinkage

Experimental procedures

Plastic shrinkage

Autogenous shrinkage

Capillary depression

Drying

Unsealed

Sealed

Sealed

Unsealed

CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

[BTJADE, 06]

[TURCRY, 2004]

Drying

35 mm

100 mm

70 mm

Capteur de pression

Céramique poreuse

SHRINKAGE INDUCED CRACKING RISK | E. Rozière et al. 281
**Experimental procedures**

**Water in concrete: definitions and experimental choices**

### Dry aggregates

<table>
<thead>
<tr>
<th></th>
<th>Constant eff. water</th>
<th>Constant add. water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Added water</td>
<td>Variable</td>
<td>-----</td>
</tr>
<tr>
<td>Effective water</td>
<td>-----</td>
<td>Variable</td>
</tr>
<tr>
<td>Total water</td>
<td>Constant</td>
<td>Variable</td>
</tr>
<tr>
<td>References</td>
<td>[AL HOZAIMY, 09],</td>
<td>[TOMA, 99],</td>
</tr>
<tr>
<td></td>
<td>[PEREIRA et al., 09],</td>
<td>[KHOON Ng &amp; CHI Ng, 11]</td>
</tr>
<tr>
<td></td>
<td>[NF EN 206-1]</td>
<td></td>
</tr>
</tbody>
</table>

- **Total water** = Water added on dry aggregates
- Absorbed aggregates
- Effective water
- Cement

**Porosity of aggregates**

\[ W_{\text{Eff}} = E_{\text{Added/Dry aggregates}} - E_{\text{Absorbed by aggregates}} \]
Early-age shrinkage

Results and analysis

Water in concrete: definitions and experimental choices

Dry aggregates

Total water = Water added using dry aggregates

Added water

Ciment

0%

Eff. water

Saturated aggregate

Water in aggr.

Added water

Ciment

100%

Eff. water

Partially saturated aggregate

Water in aggr.

Added water

Ciment

50%

Eff. water

Porosity of aggregates

Volume of paste

Eff. water

SHRINKAGE INDUCED CRACKING RISK | E. Rozière et al.
Early-age shrinkage

Results and analysis

Plastic shrinkage

Concrete mixture BV

Natural limestone gravels
Aborption ($WA_{24}$) 3.2 %
*(Standard NF EN 1097-6)*

Initial water saturation: 0%, 50% et 100%

W/C : 0.5 - E/C : 0.6

Portland cement CEM I 52.5

Drying: 20 °C – 50 % RH

Same influence of initial water saturation of gravels
Early-age shrinkage

Results and analysis

Autogenous shrinkage

- Relatively low autogenous shrinkage
- Same influence of initial water saturation of gravels: $\text{water}_{\text{paste}}/\text{cement}$ ratio
Early-age shrinkage

Results and analysis

Microstructure: evidence of absorption

- Water content of mortar and gravels

Concrete

Paste/mortar

Gravel

Water content of mortar and gravels

Degree of hydration vs. Age (h)

Water content (%) vs. Age (h)

Water content (%) vs. Age (h)

SHRINKAGE INDUCED CRACKING RISK | E. Rozière et al.
Mercury intrusion porosimetry

Age: 24 hours

- Porous structure dependent on initial saturation of gravels
Same influence of initial water saturation of gravels (cf. autogenous and plastic shrinkage) => Influence of added water on macroporosity (evidence) and interfacial transition zone (to be confirmed)
Early-age shrinkage

Results and analysis

Summary

Dry aggregates

- Granulats
- Eau
- Added water
- Cement

Saturated aggregates

- Granulats
- Eau
- Water in aggr.
- Added water
- Cement

Partially saturated aggregates

- Granulats
- Eau
- Water in aggr.
- Added water
- Cement

Porosité des Granulats

Water in paste

- Theorical water content of paste
- Actually abs. water

- 0 %
- 100 %
- 50 %
Experimental procedures

Direct tensile testing rig

New experimental method (Rozière et al., 2012)
**Experimental procedures**

### Ultrasonic monitoring of elastic modulus – *FreshCon*

- Poisson ratio: $v_{dyn}$
- Elastic modulus: $E_{dyn}$

\[
\nu_{dyn} = \frac{1}{2} \cdot \frac{v_p^2 - v_s^2}{v_p^2 - v_s^2}
\]

\[
E_{dyn} = v_p^2 \cdot \rho_c \cdot \frac{(1 + \nu_{dyn}) \cdot (1 - 2\nu_{dyn})}{1 - \nu_{dyn}}
\]

- $\rho$ density of fresh concrete,
- $v_p$ compression wave velocity,
- $v_s$ shear wave velocity.

[Reinhardt and Grosse, 2004]
Results and analysis

Ultrasonic monitoring of elastic modulus

=> Significant influence of water saturation of aggregate on elastic modulus (2-10h).
Results and analysis

Assessment of cracking sensitivity due to AUTOGENOUS shrinkage

Elastic model:
\[ \sigma(t) = \varepsilon(t) \cdot E(t) \]

\[ \sigma(t) = \varepsilon(t) \cdot E(t) \]

=> Time period when stresses due to restrained shrinkage exceed tensile strength.
Influence of water saturation on cracking due to AUTOGENOUS shrinkage

- Limestone gravels (Abs : 3,2%)
- Cement : 350 kg/m³
- E/C : 0,5

Critical period between 4 and 10 hours
Influence of water saturation on cracking due to PLASTIC shrinkage

TSTM (Temperature Stress Testing Machine): Restrained shrinkage tests

Rig for testing of self generated stress

[Hammer et al., 2007]
Conclusions

• An experimental procedure was designed to investigate the influence of water saturation of gravels of early-age shrinkage (before 24 hours) and cracking sensitivity of concrete.

• Significant variations of the plastic shrinkage and early age autogenous deformations were observed.

• Due to the kinetics of absorption of gravels, the water content remaining in cement paste was different from the effective water content.

• The evolutions of elastic modulus and tensile strength were experimentally assessed and used to compare the cracking sensitivity of the three studied concretes by evaluating the self generated stresses.
Focus on the influence of the type of aggregates on shrinkage induced cracking risk of concrete

S. Staquet, E. Rozière, A. Hamami, B. Delsaute, A. Loukili
Outline

• Experimental program
  - Mix design
  - Measurement of thermal expansion coefficient
  - Experimental approach for shrinkage induced cracking

• Early-age **autogenous** shrinkage: effect of type of aggregates
  - Autogenous shrinkage, capillary pressure, thermal expansion coefficient
  - E modulus
  - Autogenous shrinkage induced cracking

• Early-age **drying** shrinkage: effect of type of aggregates
  - Free shrinkage
  - Restraint shrinkage
### Properties of aggregates

<table>
<thead>
<tr>
<th></th>
<th>Water absorption $WA_{24}$ (%)</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sand 0/4 mm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea sand</td>
<td>0.6</td>
<td>2.58</td>
</tr>
<tr>
<td>Limestone sand</td>
<td>0.8</td>
<td>2.65</td>
</tr>
<tr>
<td><strong>Gravels 4/20 mm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz (Q)</td>
<td>0.8</td>
<td>2.59</td>
</tr>
<tr>
<td>Dense limestone (DL)</td>
<td>0.74</td>
<td>2.65</td>
</tr>
<tr>
<td>Porous limestone (PL)</td>
<td>3.2</td>
<td>2.46</td>
</tr>
</tbody>
</table>

Same water saturation degree (50%) before concrete mixing
Properties of aggregates

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>Water Absorption $W_{24}$ (%)</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/4 mm</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>Porous limestone (PL)</td>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>

Same water saturation degree (50%) before concrete mixing
## Properties of the studied concretes

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel (kg/m³)</td>
<td>1016</td>
<td>1057</td>
<td>1086</td>
</tr>
<tr>
<td>Sea sand (kg/m³)</td>
<td>378</td>
<td>378</td>
<td>378</td>
</tr>
<tr>
<td>Limestone sand (kg/m³)</td>
<td>389</td>
<td>389</td>
<td>389</td>
</tr>
<tr>
<td>Cement (kg/m³)</td>
<td>350</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Superplasticizer (Sp) (kg/m³)</td>
<td>1.25</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Effective Water: \( W_{\text{eff}} \) (kg/m³)**

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{\text{eff}} )</td>
<td>175</td>
<td>175</td>
<td>175</td>
</tr>
</tbody>
</table>

Water from superplasticizer (kg/m³)

<table>
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<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Total Water (kg/m³)

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>211</td>
<td>186</td>
<td>188</td>
</tr>
</tbody>
</table>

Water absorbed by sand: \( W_{\text{sand}} \) (kg/m³)

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{\text{sand}} )</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>

Water absorbed by gravels: \( W_{\text{gravel}} \) (kg/m³)

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{\text{gravel}} )</td>
<td>16</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Added Water: \( W_{\text{added}} \) (kg/m³)

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W_{\text{added}} )</td>
<td>172</td>
<td>159</td>
<td>161</td>
</tr>
</tbody>
</table>

\( \frac{W_{\text{eff}}}{C} \)

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{W_{\text{eff}}}{C} )</td>
<td>0.50</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\( \frac{W_{\text{added}}}{C} \)

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{W_{\text{added}}}{C} )</td>
<td>0.49</td>
<td>0.45</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**Paste Volume (L/m³)**

<table>
<thead>
<tr>
<th></th>
<th>PL</th>
<th>Q</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>288</td>
<td>288</td>
<td>288</td>
</tr>
</tbody>
</table>

---

Same water saturation degree (50%) before concrete mixing.
Properties of the studied concretes

- Support plate
- Guided rod
- Mould cap
- Ring
- PVC Mould
- Thermocouple
- Insert
- Insulated container

Autogenous deformation test device

BTJADE
[BOULAY, 06]
Properties of the studied concretes

\[ \Delta \theta_0 : \text{Temperature variation between } t \text{ and } t_0 \]
\[ \Delta U_c : \text{Displacement of the concrete.} \]
\[ \alpha_0(t_i) : \text{CTE of the concrete sample (} \alpha_0 \text{)} \]

\[ \alpha_0(t_i) = \frac{\Delta U_c(t_{i+1}) - \Delta U_c(t_i)}{L_0} \cdot \frac{\Delta \theta_0(t_{i+1})}{\Delta \theta_0(t_i)} \]
Experimental program

**Shrinkage induced cracking**

- **Setting**
  - Elastic properties (ultrasonic wave propagation)
  - Initial time

- **Deformations**
  - Thermal
  - Autogenous (BTJADE)
  - Drying (TSTM)
  - Creep (TSTM)

- **Stresses** (TSTM)
  - Restrained shrinkage

- **Tensile strength** (direct tensile testing)
  - Hardening
  - Stiffness development

- **Risk of cracking at early age**

**SHRINKAGE INDUCED CRACKING RISK | S. Staquet et al.**
TSTM (Temperature Stress Testing Machine), BATir-LGC

- Linear horizontal device
- 400 kN compression/traction jack
- Computer controlled
- Dog bone shape
  - Length = 1.3 m
  - Section = 100 x 100 mm$^2$
- Fixed and mobile heads
- Surrounded by a plastic film
  - Autogenous conditions
- Displacement sensors without contact
  - 75 cm spacing
- Thermal regulation
- Twin mould
TSTM (Temperature Stress Testing Machine)

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Free and restrained shrinkage, stress development with TSTM

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Free and restrained shrinkage, stress development with TSTM
Free and restrained shrinkage, stress development with TSTM
Experimental program

Free and restrained shrinkage, stress development with TSTM
Free and restrained shrinkage, stress development with TSTM
Free and restrained shrinkage, stress development with TSTM
Free and restrained shrinkage, stress development with TSTM
Free and restrained shrinkage, stress development with TSTM
Experimental program

CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

Free and restrained shrinkage, stress development with TSTM
Free and restrained shrinkage, stress development with TSTM

TSTM (Temperature Stress Testing Machine)

- Traction / compression
- Sealed / unsealed conditions
- Force / displacement control
- Various temperature
- Multiple stress levels
Experimental program

Free and restrained shrinkage, stress development with TSTM

\[ \varepsilon_1 = (S_1 + S_2) \times \frac{1000}{750} \]
\[ \varepsilon_2 = (S_3 + S_4) \times \frac{1000}{750} \]

CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

SHRINKAGE INDUCED CRACKING RISK | S. Staquet et al.
Restrained shrinkage, stress development with TSTM
Free shrinkage with TSTM
Restrained shrinkage, stress development with TSTM

Deformation Mould 1

Deformation threshold: \( \Delta \varepsilon_{sh} = 4 \, \mu m/m \)

Stress increase \( \Delta \sigma_i \)

\[
E_{TSTM} (t_i) = \frac{\Delta \sigma_i}{\Delta \varepsilon_{sh}}
\]
Experimental program

CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015

Free and restrained shrinkage, stress development with TSTM

\[ \varepsilon_1 = \varepsilon_{el} + \varepsilon_{cr} + \varepsilon_{th} + \varepsilon_{sh} \]

\[ \varepsilon_2 = \varepsilon_{th} + \varepsilon_{sh} \]

\[ \varepsilon_1 - \varepsilon_2 = \varepsilon_{el} + \varepsilon_{cr} \]

Measured by mold 1 of TSTM (restraint deformations)

Measured by mold 2 of TSTM (free deformations)

By knowing the elastic part, creep deformations can be obtained by the difference between deformations measured with the two molds of TSTM.
No clear correlation between autogenous shrinkage and capillary depression
Results and analysis

CTE of quartz gravels is equal to about twice the CTE of dense and porous limestone gravels.
Rapid increase of Edyn from 2 to 12-18 hours.

Evolution of dynamic modulus by ultrasound monitoring.
Influence of type of aggregates on cracking due to AUTOGENOUS shrinkage

Critical period between 6 and 10 hours
Influence of type of aggregates on cracking due to **DRYING** shrinkage

Free shrinkage (µm/m) vs. Age (h)
Influence of type of aggregates on cracking due to **DRYING** shrinkage
Influence of type of aggregates on cracking due to DRYING shrinkage

- Porous limestone
- Dense limestone
- Quartz

Cumulated strain (µm/m) vs Age (hours)
Influence of type of aggregates on cracking due to **DRYING** shrinkage

- **ft DL exp**
- **ft DL EC2**
- **stress DL computed**
- **stress DL exp**

**Dense Limestone**

SHRINKAGE INDUCED CRACKING RISK | S. Staquet et al.
Influence of type of aggregates on cracking due to **DRYING** shrinkage

**Porous Limestone**
Influence of type of aggregates on cracking due to **DRYING** shrinkage

- **ft Q exp**
- **ft Q EC2**
- **stress Q computed**
- **stress Q exp**

**Quartz**

- Restraint shrinkage
- SHRINKAGE INDUCED CRACKING RISK | S. Staquet et al.
Type of aggregates

Conclusions

• A comprehensive monitoring of the main properties of early age concrete was designed with the Temperature Stress Testing Machine to investigate the effect of dense limestone, porous limestone and quartzite gravel on the shrinkage induced cracking sensitivity of concrete.

• No effect of the type of aggregates was observed on the setting and the early age development of tensile strength.

• At very early age, until 18 hours, a very rapid increase of capillary depression, autogenous deformations, and elastic modulus was observed.

• The results showed that the risk of cracking was relatively high for dense limestone concrete and porous limestone concrete, from the ages of 6 and 10 hours respectively.
Type of aggregates

Conclusions

• **TSTM** tests were carried out in **drying conditions**. The three concretes cracked after 54 to 79 hours at similar stress levels. Under restrained conditions, moderate drying shrinkage can result in cracking of normal-strength concrete in isothermal conditions.

• Concrete made with **quartzite gravel** showed delayed risk of cracking thanks to initial expansion, and lower shrinkage magnitude. The **expansion** occurring simultaneously with initial temperature peak was attributed to **thermal deformation**. Quartzite aggregates actually show **higher coefficient of thermal expansion** than limestone aggregates.
Ring test for early cracking sensitivity of FRC: application on tunnel lining

M. Briffaut\textsuperscript{1}, F. Benboudjema\textsuperscript{2}, L. D’Aloia\textsuperscript{3}
\textsuperscript{1}Laboratoire 3SR (Grenoble)
\textsuperscript{2}LMT (Cachan)
\textsuperscript{3}CETU(Lyon)
CONTEXT

- Extension Paris subway line No.4
  - Final tunnel lining: 10m formwork (thickness ~50cm)
  - Shotcrete support

- Objectives of the study
  - Study the impact of different fibers on the "susceptibility" to cracking at early age (can fiber replace anti-cracking girds)
  - Comparison of different types of fiber
    - Polypropylene micro-fiber (PMiF)
    - Polypropylene macro-fiber (PMaF)
    - Metallic fiber (MF)

- Methodology
  - Laboratory test
  - Tunnel lining simulation
Cracking mechanism: self-restrained shrinkage

- Gradient of temperature strain and drying shrinkage between the skin and the core of the element.
Cracking mechanism: restrained shrinkage

- Thermal and autogenous restrained shrinkage

**CONTENTS**

Shotcrete
Tunnel lining

- Rock
- Shotcrete
- Tunnel lining

Crossing crack
OUTLINE

• Experimental part: Cracking sensitivity
  • Presentation of ring tests
  • Classical ring test: drying and autogeneous shrinkage
  • Thermal active ring test: thermal shrinkage
• Simulation of thermal active ring test
  • Brief model presentation
  • Thermal active ring test
• Tunnel lining cracking simulation
  • Influence of each phenomena
  • Influence of reinforcement by fibers
Experimental part: cracking sensitivity

Presentation of ring tests
Classical ring test: drying and autogeneouse shrinkage
Thermal active ring test: thermal shrinkage
Classical ring test

- Thermal shrinkage not taken into account
- No cracks for concrete with high W/C

Controlled environment (temp, RH)

- Brass: th. 3cm

Orthoradial stress profil

10cm 44cm

10cm
Thermal ring test

Thermal ring test: actif

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

Ring test before casting

Ring test after casting
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]
### FRC: concretes mix

<table>
<thead>
<tr>
<th></th>
<th>REF (Reference Mix)</th>
<th>FRC-PMiF-0.9 (0.9 kg/m³)</th>
<th>FRC-PMiF-1.8 (1.8 kg/m³)</th>
<th>FRC-PMaF</th>
<th>FRC-MF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sand (0/4)</strong></td>
<td>905</td>
<td>905</td>
<td>905</td>
<td>905</td>
<td>905</td>
</tr>
<tr>
<td><strong>Coarse aggregates (4/20)</strong></td>
<td>905</td>
<td>905</td>
<td>905</td>
<td>905</td>
<td>905</td>
</tr>
<tr>
<td><strong>Cement</strong></td>
<td>385</td>
<td>385</td>
<td>385</td>
<td>385</td>
<td>385</td>
</tr>
<tr>
<td><strong>Total water</strong></td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td><strong>Superplasticizer</strong></td>
<td>4.62</td>
<td>4.62</td>
<td>4.62</td>
<td>5.12</td>
<td>4.62</td>
</tr>
<tr>
<td><strong>Fibres (PMiF, PMaF or MF)</strong></td>
<td>0</td>
<td>0.9</td>
<td>1.8</td>
<td>7</td>
<td>43</td>
</tr>
<tr>
<td><strong>Slump (mm)</strong></td>
<td>230</td>
<td>225</td>
<td>220</td>
<td>210</td>
<td>218</td>
</tr>
<tr>
<td><strong>Entrained air (%)</strong></td>
<td>1.3</td>
<td>2.4</td>
<td>4.4</td>
<td>NM*</td>
<td>NM*</td>
</tr>
</tbody>
</table>

PMaF stands for "polypropylene macrofibres", PMiF for "polypropylene microfibres" and MF for "metal fibres".

*: Not measured.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Density</th>
<th>Type</th>
<th>Length (mm)</th>
<th>Tensile strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Fibre content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMaF</td>
<td>0.92</td>
<td>Polypropylene</td>
<td>50</td>
<td>600</td>
<td>5.0</td>
<td>7.0</td>
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<tr>
<td>PMiF</td>
<td>0.91</td>
<td>Polypropylene</td>
<td>12</td>
<td>577</td>
<td>4.2</td>
<td>0.9/1.8</td>
</tr>
<tr>
<td>MF</td>
<td>7.85</td>
<td>Steel</td>
<td>50</td>
<td>1,050</td>
<td>210.0</td>
<td>43.0</td>
</tr>
</tbody>
</table>
Classical ring test results

- No cracks under autogeneous shrinkage
- Under drying shrinkage:
  - Micro fiber: slight delay of the crack
  - Macro fiber and reinforcement: real delay of the crack
Active ring test results

Under thermal expansion of the ring:
- Micro fiber: slight delay of the crack
- Macro fiber and reinforcement: real delay of the crack
Quantitative ring tests results

### Drying shrinkage

<table>
<thead>
<tr>
<th></th>
<th>Age of cracking (h)</th>
<th>Fibre content (kg/m³)</th>
<th>Mean crack opening (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>92</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>FC-PMiF-0.9</td>
<td>95</td>
<td>0.9</td>
<td>130</td>
</tr>
<tr>
<td>FC-PMiF-1.8</td>
<td>96</td>
<td>1.8</td>
<td>130</td>
</tr>
<tr>
<td>FC-PMaF</td>
<td>104</td>
<td>7</td>
<td>120</td>
</tr>
<tr>
<td>RC-MF</td>
<td>109</td>
<td>43</td>
<td>100</td>
</tr>
<tr>
<td>Steel reinforcement (1 rebar $\phi 8$)</td>
<td>98</td>
<td>0</td>
<td>90</td>
</tr>
</tbody>
</table>

### Thermal expansion

<table>
<thead>
<tr>
<th></th>
<th>Age of cracking (h)</th>
<th>Fibre content (kg/m³)</th>
<th>Number of cracks</th>
<th>Crack opening (µm) measured at 50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>80</td>
<td>0</td>
<td>1</td>
<td>700</td>
</tr>
<tr>
<td>FRC-PMiF-0.9</td>
<td>83</td>
<td>0.9</td>
<td>1</td>
<td>550</td>
</tr>
<tr>
<td>FRC-PMiF-1.8</td>
<td>83</td>
<td>1.8</td>
<td>1</td>
<td>450</td>
</tr>
<tr>
<td>FRC-PMaF</td>
<td>94</td>
<td>7</td>
<td>2</td>
<td>400 and 250</td>
</tr>
<tr>
<td>FRC-MF</td>
<td>97</td>
<td>43</td>
<td>2</td>
<td>225 and 150</td>
</tr>
<tr>
<td>Steel reinforcement (1 rebar $\phi 8$)</td>
<td>91</td>
<td>0</td>
<td>2</td>
<td>200 and 150</td>
</tr>
</tbody>
</table>
Simulation of thermal active ring test

Brief model presentation
Thermal active ring test
Focus on coupling between creep and damage
Global strategy

« Standardized » test

Active ring test

Hydration  Creep  Shrinkage

Chemo-thermo-mechanical model

Thermal strains  Mechanical prop. Evol.

Coupling + Representatives boundaries conditions + effect of fibers

Structures modelling
## Example of standardized test

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without fiber</td>
<td>3.60</td>
</tr>
<tr>
<td>PMiF [0.9 Kg/M³]</td>
<td>3.8</td>
</tr>
<tr>
<td>PMiF [1.8 Kg/M³]</td>
<td>3.82</td>
</tr>
<tr>
<td>PMaF [7 Kg/M³]</td>
<td>4.07</td>
</tr>
<tr>
<td>Steel [43 Kg/M³]</td>
<td>4.78</td>
</tr>
</tbody>
</table>

### Tensile strength by indirect test

- Polypro Micro fibers
- Polypro Macro fibers
- Metallic fibers
- Without fibers

---

RING TEST FOR EARLY CRACKING SENSITIVITY OF FRC: APPLICATION ON TUNNEL LINING | M. Briffaut et al.
Chemo-thermal model

Heat equation with source

\[ C \frac{dT}{dt} = \nabla(k \nabla T) + L \dot{\xi} \]

- \( C = C (\xi, T, \text{concrete mix}) = \) Volumetric thermal capacity
- \( k = k (\xi, T, \text{concrete mix}) = \) Thermal conductivity
- \( L = L (\text{concrete mix}) = \) Total heat release

Hydration degree evolution

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

\[ \dot{\xi} = \bar{A}(\xi) \exp \left( -\frac{E_a}{RT} \right) \]

Mechanical parameters evolution [De Schutter et Taerwe, 96]

\[ X(\xi) = X_\infty \left( \frac{\xi(t) - \xi_0}{\xi_\infty - \xi_0} \right)^{\alpha_x} \]

pour \( \xi > \xi_0 \)

Autogeneous and thermal strains

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

\[ \dot{\varepsilon}_{ij}^{au} = \kappa \dot{\xi} \delta_{ij} \]

pour \( \xi > \xi_0 \)

\[ \dot{\varepsilon}_{ij}^{th} = \alpha \dot{T} \delta_{ij} \]
Creep model

Rheological modelling

- Kelvin-Voigt chains (KV):
  \[ \sigma(t) = \eta_{bc} \dot{\varepsilon}_{bc} + \eta_{bc}^n \dot{\varepsilon}_{bc} \]
  \[ \tau_{bc} = \frac{\eta_{bc}^i}{k_{bc}^i(\xi, T)} = \text{const} \]

- Differential equation of one KV:
  \[ \tau_{bc} \ddot{\varepsilon}_{bc} + \left( \tau_{bc} \frac{k_{bc}^i(\xi, T)}{k_{bc}^i(\xi, T)} + 1 \right) \dot{\varepsilon}_{bc} = \frac{\dot{\sigma}}{k_{bc}^i(\xi, T)} \]
Mechanical model

Strains decomposition

\[ \tilde{\sigma} = E(\xi)\dot{\varepsilon}_e = E(\xi)(\dot{\varepsilon}_{tot} - \dot{\varepsilon}_{bc} - \dot{\varepsilon}_{itt} - \dot{\varepsilon}_{au} - \dot{\varepsilon}_{th}) \]

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

\[ \tilde{\varepsilon} = \sqrt{\langle \varepsilon_e \rangle_+} + \beta \langle \varepsilon_{bc} \rangle_+ \]

Damage threshold

\[ \kappa_0 = \frac{f_{tx}}{E_\infty} \left( \frac{\xi - \xi_0}{\xi_\infty - \xi_0} \right)^{c-a} \]

Damage variable evolution [Nechnech, 00]

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

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

✓ For high fiber content
  ✓ Softening phase -> hardening phase
  ✓ Fracture energy could not be easily determined
✓ Hypothesis: for low fiber content
  ✓ Concept of fracture energy still relevant

<table>
<thead>
<tr>
<th></th>
<th>Fracture energy (J.m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>100</td>
</tr>
<tr>
<td>FRC-PMiF-0.9</td>
<td>230</td>
</tr>
<tr>
<td>FRC-PMaF</td>
<td>280</td>
</tr>
<tr>
<td>FRC-MF</td>
<td>1,200</td>
</tr>
</tbody>
</table>

Fracture energy values [Bei Xing et al., 04]  [Barros and Sena Cruz, 01]
Validation on thermal ring test

- Concrete = homogeneous material -> $\beta = 0.4$
- Good global agreement between experimental data and simulation
- No creep increase due to fibers
Tunnel lining cracking simulation

Influence of each phenomena

Influence of reinforcement by fibers
Tunnel lining simulations

- Calibration with Temperature in situ
- 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

- High influence of creep (as expected)
- Main phenomena involve in cracking:
  - Thermal evolution
  - Drying -> only skin crack

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

Damage field due to drying shrinkage after 1,000 days
Fibers influence

- Slight reduction of strain gap (cracks) with PMiF
- No crossing crack predict with macro fibers
- Decrease of transport properties thought cracks with:
  - micro fibers: 38%
  - Macro fibers: 100%!!! -> take care of pumping consideration
Tunnel lining geometry influence

- Smooth interface
  - Damage and permeability thought cracks decrease (65%)  
- Lower thickness
  - Temperature evolution and cracks decrease  
- Permeability decrease 50%

Damage field without fibres (REF)

Damage field with a smooth interface between lining and shotcrete

Damage field with a 30-cm concrete thickness
Conclusion

• A global strategy coupling complex and innovative test with chemo-thermo mechanical modelling was used to study the influence of fibers on cracking of massive tunnel lining.

• On laboratory test:
  • Use of PMiF does not really delay cracks
  • Use of PMaF delays and distribute cracks

• Coupling coefficient between creep and damage is explained by strains incompatibilities

• Main phenomena involves in tunnel lining cracking is thermal shrinkage
  • Use of PMaF could avoid cracks (at least decrease strongly transport properties)
  • Use of PMiF is useless to prevent early age cracking
  • Decrease tunnel thickness limit temperature shrinkage and reduce crack openings
Avoiding thermal cracks in mass concrete: problems, solutions and doubts

Selmo Kuperman\textsuperscript{1,*}
\textsuperscript{1}DESEK, São Paulo, Brasil
Types of structures prone to thermal cracks

dams and hydropowerplants
Hydroelectric powerplant under construction in Brazil (2015)

~ 2,900,000 m$^3$ = CVC + RCC
RCC and CVC being placed in Brazilian hydroelectric powerplants

RCC and CVC at Lajeado HPP (1998)

Itaipu powerhouse – 2nd stage construction (2003)
Types of structures prone to thermal cracks

foundation of wind towers
Different types of foundations for wind towers

Wind park Casa Nova (2013) – 436m³

Wind park Uniao dos Ventos (2012) – 260m³
Types of structures prone to thermal cracks

foundation blocks – industrial and residential
Pumped concrete for the foundations of industrial and residential buildings

1390 m³
Foundations of residential buildings

390 m³ - SCC

AVOIDING THERMAL CRACKS IN MASS CONCRETE | S. Kuperman
Types of structures prone to thermal cracks

concrete bunkers for radioactive equipments
Concrete bunkers for radioactive equipments
Problems

- cracks due to thermal stresses
- cracks due to DEF (in most cases together with ASR)
Cracks due to DEF and ASR in foundation blocks of different buildings

ASR + DEF

DEF

ASR + DEF
Cracks due to thermal stresses
Demolition of a concrete foundation block at an industry due to thermal cracking
Thermal cracking at Upper Stillwater dam (USA)
Solutions

thermal stresses analysis – pre-cooling, post-cooling and changes of the construction scheme
Thermal stresses analysis

3D FEM of temperatures coupled with stresses (software B4Cast)

Example: Cracked spillway
Thermal stresses analysis
3D FEM of temperatures coupled with stresses
Example: Isotherms
Thermal stresses analysis (B4Cast software)
3D FEM of temperatures coupled with stresses.
Example: Foundation block 17.5m x 9m x 2.75m
### 3D FEM thermal stresses analysis

**Mix design**

#### TRAÇÃO A

<table>
<thead>
<tr>
<th>Material</th>
<th>Fornecedor</th>
<th>Consumo (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cimento CPIII</td>
<td></td>
<td>420</td>
</tr>
<tr>
<td>Areia Fina</td>
<td>Quartzo</td>
<td>480</td>
</tr>
<tr>
<td>Pedrisco Misto</td>
<td>Granito</td>
<td>441</td>
</tr>
<tr>
<td>Brita 1</td>
<td>Granito</td>
<td>900</td>
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<tr>
<td>Água</td>
<td></td>
<td>165</td>
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<tr>
<td>Aditivo 1</td>
<td></td>
<td>2,100</td>
</tr>
<tr>
<td>Aditivo 2 = Policarboxilato</td>
<td></td>
<td>1,102</td>
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</table>

#### TRAÇÃO B

<table>
<thead>
<tr>
<th>Material</th>
<th>Fornecedor</th>
<th>Consumo (kg/m³)</th>
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<tbody>
<tr>
<td>Cimento CPIII</td>
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<td>386</td>
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<tr>
<td>Metacaulim</td>
<td>Metacaulim</td>
<td>34</td>
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<tr>
<td>Areia Fina</td>
<td>Quartzo</td>
<td>493</td>
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<td>Pedrisco Misto</td>
<td>Basalto</td>
<td>410</td>
</tr>
<tr>
<td>Brita 0</td>
<td>Basalto</td>
<td>100</td>
</tr>
<tr>
<td>Brita 1</td>
<td>Basalto</td>
<td>772</td>
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<tr>
<td>Água</td>
<td></td>
<td>48</td>
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<tr>
<td>Gelo</td>
<td></td>
<td>130</td>
</tr>
<tr>
<td>Aditivo 1</td>
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<td>2,100</td>
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<tr>
<td>Aditivo 2 = Policarboxilato</td>
<td></td>
<td>1,102</td>
</tr>
</tbody>
</table>
Thermal stresses analysis
Concrete properties
Example: Foundation block

<table>
<thead>
<tr>
<th>Propriedade térmica</th>
<th>Traço A</th>
<th>Traço B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calor específico (kJ/kg.°C)</td>
<td>0,97</td>
<td>0,99</td>
</tr>
<tr>
<td>Condutividade térmica (kJ/m.h.°C)</td>
<td>8,83</td>
<td>8,77</td>
</tr>
<tr>
<td>Coeficiente de dilatação térmica ((10^-6/°C)</td>
<td>9,3</td>
<td>9,4</td>
</tr>
</tbody>
</table>
Thermal stresses analysis
3D FEM of temperatures coupled with stresses
Example: Foundation block
Thermal stresses analysis
Chosen points for monitoring temperatures
Example: Foundation block
Thermal stresses analysis
Example: Cases studied for a foundation block

<table>
<thead>
<tr>
<th>Structure</th>
<th>Case</th>
<th>Mix Design</th>
<th>Placing temperature (°C)</th>
<th>Lift height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation block</td>
<td>I</td>
<td>A</td>
<td>15</td>
<td>2,75</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>III</td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IV</td>
<td>B</td>
<td>15</td>
<td>2,75</td>
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<tr>
<td></td>
<td>V</td>
<td></td>
<td>20</td>
<td></td>
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<tr>
<td></td>
<td>VI</td>
<td></td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
Thermal stresses analysis
Example: Cases studied for a foundation block

Evolution of temperatures-Placing temperature=25°C- (Mix A)
Thermal stresses analysis
Example: Cases studied for a foundation block
Thermal stresses analysis

Influence of placement temperatures on the maximum temperatures to be reached at the concrete block

Effect of placing temperature on the maximum temperature (Mix design A)

Effect of placing temperature on the maximum temperature (Mix design B)
Thermal stresses analysis

Example: Influence of placement temperatures on tensile stresses

Evolution of temperatures - Placing temperature = 25°C (Mix A)

Evolution of major principal stresses - Placing Temperature = 25°C (Mix A)

Crack
Thermal stresses analysis

Example: Influence of placement temperatures on tensile stresses

Evolution of major principal stresses – Placing Temperature=25°C (Mix A)

Evolution of major principal stresses – Placing Temperature=15°C (Mix A)

Crack

Does not crack

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Thermal stresses analysis
Effect of placement temperatures on the maximum tensile stresses

Mix B

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Thermal stresses analysis
Effect of placement temperatures on the maximum tensile stresses at a foundation block

**f_{ck} = 30MPa at 28 days**

<table>
<thead>
<tr>
<th>Temperatura de Lançamento (°C)</th>
<th>Tensões Máximas (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>1,0</td>
</tr>
<tr>
<td>14</td>
<td>2,42</td>
</tr>
<tr>
<td>15</td>
<td>2,36</td>
</tr>
<tr>
<td>16</td>
<td>2,33</td>
</tr>
<tr>
<td>17</td>
<td>2,14</td>
</tr>
<tr>
<td>18</td>
<td>2,02</td>
</tr>
<tr>
<td>19</td>
<td>3,37</td>
</tr>
<tr>
<td>20</td>
<td>3,30</td>
</tr>
<tr>
<td>21</td>
<td>3,37</td>
</tr>
<tr>
<td>22</td>
<td>3,00</td>
</tr>
<tr>
<td>23</td>
<td>3,02</td>
</tr>
<tr>
<td>24</td>
<td>2,86</td>
</tr>
<tr>
<td>25</td>
<td>3,71</td>
</tr>
<tr>
<td>26</td>
<td>3,69</td>
</tr>
<tr>
<td>27</td>
<td>4,01</td>
</tr>
<tr>
<td>28</td>
<td>4,60</td>
</tr>
<tr>
<td>29</td>
<td>4,46</td>
</tr>
<tr>
<td>30</td>
<td>4,39</td>
</tr>
<tr>
<td>31</td>
<td>4,25</td>
</tr>
</tbody>
</table>

**Legend**
- A(h=20cm)
- B(h=40cm)
- C(h=60cm)
- D(h=80cm)
- E(h=100cm)
- f_{ck} (FS=1,0)
- f_{ck}(FS=1,2)
Thermal stresses analysis
Results of a foundation block analysis: pre-cooling the concrete and imposing maximum placement temperatures for different heights

Nota: TL=Temperatura de lançamento do concreto; \( V_c = \) Volume de concreto teórico em cada zona de temperatura de lançamento.
Thermal stresses analysis
Results of a foundation block analysis: pre-cooling the concrete and imposing maximum placement temperatures for different heights

- TL ≤ 16°C
- V ~ 90 m³
- H = 0.6 m

- TL ≤ 23°C
- V ~ 120 m³
- H = 0.8 m

- TL ≤ 30°C
- V ~ 180 m³
- H = 1.0 m

AVOIDING THERMAL CRACKS IN MASS CONCRETE | S. Kuperman
Thermal stresses analysis
Maximum placement temperatures calculated for the Intake of a hydropower plant
Thermal stresses analysis

Maximum placement temperatures calculated for a foundation block of a commercial building
Thermal stresses analysis
Placement temperature of a pre-cooled concrete - Heat balance

<table>
<thead>
<tr>
<th>Materiais</th>
<th>Consumo (kg/m³)</th>
<th>Calor esp. (kcal/kg.C)</th>
<th>q = mc (kcal/m³.C)</th>
<th>E (kcal/m³)</th>
<th>Ti (°C)</th>
<th>Tf (°C)</th>
<th>Ti - Tf</th>
<th>Quant. Calor (kcal/m³)</th>
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</thead>
<tbody>
<tr>
<td>Mistura</td>
<td>Cimento</td>
<td>321</td>
<td>0,159</td>
<td>51,04</td>
<td>51,04</td>
<td>60,0</td>
<td>60,0</td>
<td>3062,34</td>
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<tr>
<td></td>
<td>Areia (quartzo)</td>
<td>356</td>
<td>0,191</td>
<td>68,00</td>
<td>68,00</td>
<td>30,0</td>
<td>30,0</td>
<td>2039,88</td>
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<tr>
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<td>Areia (granítica)</td>
<td>448</td>
<td>0,176</td>
<td>78,85</td>
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<td>30,0</td>
<td>30,0</td>
<td>2365,44</td>
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<tr>
<td></td>
<td>Brita 0 (granítica)</td>
<td>156</td>
<td>0,176</td>
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<td>30,0</td>
<td>30,0</td>
<td>823,68</td>
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<tr>
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<td>Brita 1 (granítica)</td>
<td>852</td>
<td>0,176</td>
<td>156,99</td>
<td>156,99</td>
<td>30,0</td>
<td>30,0</td>
<td>4709,76</td>
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<tr>
<td></td>
<td>Água</td>
<td>27</td>
<td>1,000</td>
<td>26,83</td>
<td>26,83</td>
<td>25,0</td>
<td>25,0</td>
<td>670,77</td>
</tr>
<tr>
<td></td>
<td>Aditivo</td>
<td>2,25</td>
<td>1,000</td>
<td>2,25</td>
<td>2,25</td>
<td>25,0</td>
<td>25,0</td>
<td>56,25</td>
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<tr>
<td></td>
<td>Gelo</td>
<td>121,4</td>
<td>0,500</td>
<td>60,70</td>
<td>60,70</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
</tr>
<tr>
<td></td>
<td>Fusão do gelo</td>
<td>121,4</td>
<td>0,000</td>
<td>0,00</td>
<td>0,00</td>
<td>0,0</td>
<td>0,0</td>
<td>-9712,75</td>
</tr>
<tr>
<td></td>
<td>Gelo/água</td>
<td>121,4</td>
<td>1,000</td>
<td>121,4</td>
<td>121,4</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
</tr>
<tr>
<td></td>
<td>Umidade miúdo areia quartzo (5%)</td>
<td>17,8</td>
<td>1,000</td>
<td>17,80</td>
<td>17,80</td>
<td>30,0</td>
<td>30,0</td>
<td>534,00</td>
</tr>
<tr>
<td></td>
<td>Umidade miúdo areia granítica (1%)</td>
<td>4,5</td>
<td>1,000</td>
<td>4,48</td>
<td>4,48</td>
<td>30,0</td>
<td>30,0</td>
<td>134,40</td>
</tr>
<tr>
<td></td>
<td>Umidade do graúdo (1%)</td>
<td>10,5</td>
<td>1,000</td>
<td>10,48</td>
<td>10,48</td>
<td>30,0</td>
<td>30,0</td>
<td>314,40</td>
</tr>
<tr>
<td></td>
<td>Mistura Betoneira</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2000,00</td>
</tr>
</tbody>
</table>

Equivalente em água (E=mc.1°C) = 626,29 kcal/m³
Quantidade total de calor (Q) = 6998,17 kcal/m³.C
Temperatura de saída do concreto da betoneira (Q / E) =
Ganho de temperatura no transporte até o local de lançamento =
Temperatura de lançamento do concreto -

\[ Tc = 11.2 \, ^\circ C \]
\[ Ti = 2.0 \, ^\circ C \]
\[ TL = 13.2 \, ^\circ C \]
Temperature measurements with thermocouples at a foundation block of a commercial building
Measured and calculated temperatures of a foundation block

Bloco de Fundação - Temperaturas - (Termômetro 3)

Bloco de Fundação - Temperaturas - (Termômetro 4)

Bloco de Fundação - Temperaturas - (Termômetro 5)

Bloco de Fundação - Temperaturas - (Termômetro 7)
Foundation blocks - Pre-cooling concrete with ice
Pre-cooling of concrete

Steel tubes covered with ice at the 2nd stage Itaipu HPP (2003)

Ice plant at Lajeado HPP (1998)
Production of ice flakes at a hydropowerplant in Brazil (2015)
Lift heights at hydropower plants in Brazil

Conventional concrete (CVC) block construction with 2m lift height and 0,5m high sub lifts (HPP in Brazil).

Sloped lift layer (0,3m) of RCC placement at Lajeado HPP (Brazil).
Doubts

How precise are stresses calculations?
Thermal stresses analysis
Data needed for calculations

- Geometry of the structure;
- Concreting plan and construction schedule (mainly placement intervals and lift heights);
- Concrete mix design;
- Concrete properties: compressive strength, tensile strength, modulus of elasticity, Poisson`s ratio, creep, density;
- Thermal properties of concrete and its components: specific heat, thermal conductivity, coefficient of thermal expansion, heat of hydration of cement, adiabatic temperature rise of concrete;
- Mechanical and thermal properties of the restraining members (foundation and walls, such as rock, concrete, soil);
- Ambient conditions of the site (mainly temperatures and wind);
- Curing conditions of the concrete;
- Formwork properties.
Thermal stresses analysis
Which is the accuracy of available data?

✓ Modulus of elasticity (10%?)

✓ Tensile strength (Direct test? Splitting test? Strain capacity?)

✓ Coefficient of thermal expansion of concrete (can vary between 0,1 and 0.9x10^{-6}/°C? – according to Tanesi, TRB)

✓ Adiabatic temperature rise

✓ Heat of hydration

✓ Concrete creep

✓ Restraint conditions (mainly modulus of elasticity) – try measurements in the structure to check the effects as the height increases and compare with FEM calculations.
Thermal stresses analysis

Proposition for different Factors of Safety on the calculations of thermal stresses, supposing that all construction details and ambient conditions are available, such as placement intervals, curing conditions, lift heights, construction schedule, etc.

Proposition of Progressive Factors of Safety

- **FS = 1,0 = never**
- **FS = 1,1 = when modulus of elasticity, strengths evolutions with time and thermal properties of concrete are available**
- **FS = 1,2 = when modulus of elasticity, strengths evolutions with time, heat of hydration of cement and some thermal properties of concrete aggregates are available**
- **FS = 1,3 = when compressive strength is available**
Thermal stresses analysis
Creep: how to consider?

a) Consider modulus of elasticity of concrete only after 1 day or only after the maximum temperature has been attained?

b) Consider creep as either a decrease in the modulus of elasticity or an increase in the tensile strength of concrete?
New Admixtures to control temperatures: are they useful?

Cement pastes calorimetric tests

<table>
<thead>
<tr>
<th>SAMPLES</th>
<th>SETTING TIME</th>
<th>TEMPERATURA FINAL °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MURAPLAST FK 118</td>
<td>21:36:00 26:30:00</td>
<td>62.61</td>
</tr>
<tr>
<td>0.6% MURAPLAST FK118 + 0.65% MURASIT ECO 200</td>
<td>119:27:00 125:45:00</td>
<td>45.38</td>
</tr>
<tr>
<td>0.6% MURAPLAST FK 118 + 0.8% MURASIT ECO 200</td>
<td>152:12:00 157:54:00</td>
<td>42.68</td>
</tr>
<tr>
<td>0.6% MURAPLAST FK 118 + 1,0% MURASIT ECO 200</td>
<td>207:27:00 212:18:00</td>
<td>35.05</td>
</tr>
</tbody>
</table>
Issues on modelling cracking of massive concrete structures at early-age

Farid BENBOUDJEMA¹, Aveline DARQUENNES¹ et al.
¹LMT-Cachan/ENS-Cachan/CNRS/Université Paris Saclay
Mismatch of autogeneous/drying strains and coefficient of thermal expansion

Between aggregates and cement paste
Mismatch of autogeneous/drying strains and coefficient of thermal expansion

Tensile stresses in cement paste / Compressive stresses in Aggregates

Plot of Mazars equivalent strain

Diffuse cracking? Ambient conditions?, concrete mix, …?
Stresses generated by self-restraint

Autogeneous shrinkage

Thermal shrinkage

Drying shrinkage

\[ D_w = 10^{-9}/10^{-12} \text{ m}^2\text{s}^{-1} / D_{th} = 10^{-6} \text{ m}^2\text{s}^{-1} \]

Superficial cracking mainly driven by gradient of temperature

Ambient conditions, concrete mix, structure size, formwork
Stresses generated by external restraint

\[ T(t), \varepsilon^{th}(t) \]

\[ E(t) \]

\[ \varepsilon^{au}(t) \]

\[ \sigma(t) \]

Crossing cracks driven by the maximum reached temperature

Ambient conditions, concrete mix, structure size, formwork
Cracking in massive structures

Concrete walls casted during the construction of concrete containments (nuclear powerplant)

![Temperature vs Time Chart](image1)

- Itthuralde (1989)
- 8 cracks, (1x40 µm) + (4x100 µm) + (2x200 µm) + (1x500 µm)
- Great reduction of the tightness

![Diagram of dimensions](image2)

$$Q \approx \frac{w^3(p^2 - p_a^2)}{24 \mu L r T}$$

Great reduction of the tightness
Design code in Europe

Eurocode EN 1992-1-1
Common building § 2.3.3
Deformations of concrete

Consideration should also be given to:
• minimising deformation and cracking due to early-age movement, creep and shrinkage through the composition of the concrete mix;
• if restraints are present, ensuring that their influence is taken into account in design.

No additional information in EN 1992-2 (concrete bridges)

EN 1992-3 (Liquid retaining and containment structures)
Restriction factors, depending on the configuration

Guidelines in Europe (CIRIA …), design code outside Europe (JCI, ACI …)
What we need to predict cracking?
Phenomenological and macroscopic approach

Hydration (thermo-activation)

\[ \dot{\xi} = \tilde{A}(\xi) e^{-E_a/RT} \]

Heat + exothermy

\[ C \frac{\partial T}{\partial t} = \nabla(k \nabla T) + L \dot{\xi} \]

Thermal + Autogeneous shrinkage

\[ \dot{\epsilon}^{th} = \alpha \dot{T} \]
\[ \dot{\epsilon}^{au} = \kappa \dot{\xi} \]

Drying and drying shrinkage

\[ D_w = 10^{-9}/10^{-12} \text{ m}^2\text{s}^{-1} \quad D_{th} = 10^{-9} \text{ m}^2\text{s}^{-1} \]

Couplings

\[ \dot{\sigma} = E(\xi)(1 - D)(\dot{\epsilon} - \dot{\epsilon}^{th} - \dot{\epsilon}^{au} - \dot{\epsilon}^{bc}) \]

\[ f(\sigma, \xi) \leq 0 \]

Young modulus and tensile strength vary with hydration degree.

Basic, drying creep ...

\[ \dot{\epsilon}^{i}_{bc} \tilde{\epsilon}^{i}_{bc} + \left( \frac{\dot{\epsilon}^{i}_{bc}(\xi)}{k^{i}_{bc}(\xi)} + 1 \right) \dot{\epsilon}^{i}_{bc} = \frac{\dot{\sigma}}{k^{i}_{bc}(\xi)} \]

\[ \tilde{\sigma} = \eta^{i}_{bc}(\xi) \dot{\epsilon}^{i}_{bc} \]

Mechanisms for creep and shrinkage are still not well identified ...
Hydration
Creeps
Shrinkages
Chemo-physical modelling
Heat, drying
Properties evolution
Couplings + Boundary conditions + Variability

« Complex » tests (validation)

« Classical » tests (identification)

« Fundamental » Research

CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015
Some results on structures
Creep and CTE effects
Comparison of basic creep in direct tension and compression

Creep in compression is higher than in tension

Creep in tension is higher than in compression

Most of time, data are available in compression
Code models suppose same creep

A. Hilaire PhD thesis
Influence of creep and its asymmetry
Influence of creep and its asymmetry

\[ \alpha = \frac{\text{Creep in tension}}{\text{Creep in compression}} \]

Same effects for other stresses (gradient)
Influence of creep and its asymmetry

\[ \alpha = \frac{\text{Creep in tension}}{\text{Creep in compression}} \]

Damage (cracking) fields

\[ \epsilon_{bc} = 0 \]

\[ \alpha_{bc} = \frac{1.69}{3} \]

\[ \alpha_{bc} = 1.69 \]

\[ \alpha_{bc} = 3 \times 1.69 \]
Effect of CTE variations at early age

[De Schutter, 1996]
Effect of CTE variations at early age

Same effects for other stresses (gradient)

A. Hilaire PhD thesis
Effect of CTE variations at early age

MODELLING CRACKING OF MASSIVE CONCRETE STRUCTURES AT EARLY-AGE | F. Benboudjema et al.

ECOBA mock-up

Experimental: △ Sensor 1 ○ Sensor 3
LMT calorimeter: -- Sensor 1 --- Sensor 3
[Briffaut, 2010]: --- Sensor 1 ---- Sensor 3
Effect of CTE variations at early age
Mismatch of autogeneous/drying shrinkage and coefficient of thermal expansion

On the “structural scale”
Reinforced concrete ties (HA 12)

1 m

10 cm

F

A. Michou PhD thesis

1x1 mm² engraving

Embedded optical fiber

A. Michou PhD thesis
Reinforced concrete ties (HA 12)

Identification of material parameters on compression/tension tests for concrete, steel/concrete interface (pull-out)

Numerical simulations
Reinforced concrete ties (HA 12)

\[ \epsilon_{tot} = \epsilon_{elas} + \epsilon_{re} + \epsilon_{rd} + \epsilon_{fp} + \epsilon_{fd} \]

Shrinkage tests
Creep tests

Size effect on shrinkage

Numerical simulations
Reinforced concrete ties (HA 12)

Prior to loading, effect of shrinkage restraint

The effect is significant and depends on the reinforcement ratio

Of course reinforcement has a positive impact!
Mismatch of autogeneous/drying shrinkage and coefficient of thermal expansion

Meso-scale approach
Volumic finite elements

Adapted mesh

Interface elements

Truss elements

Non-adapted mesh (projection of properties on a mesh)

No interface elements

Interface elements

M. Briffaut PhD thesis

Collaboration with C. Laborde (Univ. Pau)

Collaboration with J.-B. Colliat (Univ. Lille)
✓ Influence of the concrete mix (ordinary and high performance)
✓ Influence of mechanical boundary conditions and temperature evolution
✓ Influence of the concrete mix (ordinary and high performance)

✓ Influence of mechanical boundary conditions and temperature evolution

MODELLING CRACKING OF MASSIVE CONCRETE STRUCTURES AT EARLY-AGE | F. Benboudjema et al.
Evolution of the damage field (D) during hydration (in the core)

- Initiation around aggregates
- HPC undergoes larger damage since autogeneous shrinkage and temperature increase are larger

HPC

OC

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<thead>
<tr>
<th>t</th>
<th>0</th>
<th>1</th>
<th>D</th>
</tr>
</thead>
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<tr>
<td>240</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Finite element calculations volumetric mixing law

- Significant decrease of mechanical material parameters and shape of the behavior law, similar to what it is observed at high temperature
- Creep of cement paste has a great positive effect
- Larger (unrealistic) reduction in the case of HPC (not presented): loss of “potentiality” for better properties with a loading in tension?
Conclusions

- Autogeneous shrinkage induces in an uniform manner damage due to strains incompatibilities between cement paste and aggregates
- Shrinkage restraint of steel rebars can be significant
- Mastering asymmetry of creep in tension/compression is of great importance! But not CDT evolution at early-age?

Perspectives

- Effect of self-healing?
- Adaptation of the model to mineral admixtures (slag …) with the study of the impact of expansion
Early age modeling of low-pH concrete: Application to the behavior of nuclear waste storage structures

Laurie Buffo-Lacarrière¹, Alain Sellier¹

¹Université de Toulouse; UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des Constructions); 135, avenue de Rangueil; F-31 077 Toulouse Cedex 04, France
Context: Nuclear waste storage structures

Deep underground repository:
- 500 m underground tunnels
- Callovo-Oxfordian geological formation

⇒ Rock = barrier for radio-nuclide transport
⇒ Concrete used for the mechanical stability of the storage
**Tunnels sealing systems**

High-expansion bentonite + Concrete

⇒ Bentonite: barrier for nuclides

⇒ Concrete: bentonite confinement

*But: high pH leads bentonite to lose its confinement properties*

⇒ Use of low pH concrete

---

**Massive concrete block casted to close the tunnel**
**Tunnels sealing systems**

Low pH concrete:

=> high substitution of cement by mineral additions

<table>
<thead>
<tr>
<th>(W/C=0,43)</th>
<th>% in binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I</td>
<td>20</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>32</td>
</tr>
<tr>
<td>Slag</td>
<td>48</td>
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</table>

**Study objectives**

Prediction of paste evolution for low pH concrete

Simulation of the induced early age behaviour in the blocks of sealing system
Driving process:
Cement hydration
⇒ Temperature increase
⇒ Water consumption
⇒ Hydrate development

Mechanical response:
⇒ Stresses induced by internal or external restraining
⇒ Variation of mechanical properties

Multiphasic hydration model

Model adapted to low pH cement

Mechanical model with creep + Chemo-mechanical couplings

Early age structure + Restraining = Cracking risk
Outline

• General principle of early age modeling
• Hydration model for composed binder
• Application of the early age THCM model to nuclear waste storage structures
Hydration model for composed binders
Principle of multiphasic model

- Coupled solving of hydration, temperature and water variations

- Strong coupling T/C and H/C

**Principle of multiphasic model**

- Coupled solving of hydration, temperature and water variations

  - Strong coupling $T/C$ and $H/C$

\[
\dot{\alpha} = F(\tilde{\alpha}, W, T, CH)
\]
\[
\dot{W} = \text{div}(D_w \cdot \text{grad}W) + f \cdot Q_{th}^W \cdot \dot{\alpha}
\]
\[
\rho c \cdot \dot{T} = \text{div}(\lambda \cdot \text{grad}T) + f \cdot Q_{th}^T \cdot \dot{\alpha}
\]

**Originality:** separate kinetic law for cement and additions

**MATERIAL**

**ENVIRONMENT**

- RH Cure
- Ventilation
- Ext. Temp
- Formwork
- Clinker
- Hydration degree
- Additions
- Hygral "activation"
- Water content
- Thermal activation
- Temperature

EARLY AGE MODELING OF LOW-pH CONCRETE | L. Buffo-Lacarrière and A. Sellier
Kinetic law for each anhydrous

- Individual law needed due to different activation energies
  - Temperature variations have more effects on additions’ kinetic

- Phenomenological law

\[ \dot{\alpha}_i = K_i \cdot g_i(\alpha, W) \cdot \Pi_i(\bar{r}) \cdot h_i(T) \cdot s_i(Ca) \]

Chemical activation of dissolution

Activation of precipitation (addition reactions)

Water accessibility to anhydrous

Thermal activation
Interaction clinker/additions

- Strong coupling between kinetics and T/W balance equation
  - Reactions influence T and W variations
  - In return T and W variations affect each kinetic law

- Additional internal variables
  - Porosity
  - Calcium hydroxide content (effect on additions’ kinetic)

Specificities of slag blended cement

Calcium needed to produce slag hydrates can come from:
- CaO present in anhydrous slag
- CH produced by cement hydration

Hydrate stoichiometry is affected by portlandite content

⇒ Necessity of a scalable stoichiometry of CASH produced by slag
Stoichiometry of slag hydrates

\[ \frac{\partial C_L}{\partial \alpha_L} = k_L(t) \frac{\partial C_{\text{tot}}}{\partial \alpha_L} \quad \text{and} \quad \frac{\partial CH}{\partial \alpha_L} = k_C(t) \frac{\partial C_{\text{tot}}}{\partial \alpha_L} \]

 Calcium taken from CH when % of slag decreases

Higher C/S ratios for CASH with CH

Distribution coefficient function of the probability to encounter CH and CaO

\[ \frac{C}{S_L}(t) = k_L(t) \frac{C}{S_{lp}} + k_C(t) \frac{C}{S_C} \]
Validation on experimental results

- Validation of stoichiometry of slag hydrates
  - Measurements of C/S ratios for slag blended cement (Richardson 1992)
  - Calculation of the mean C/S ratio of paste from hydration model

- Validation of kinetic
  - Fitting parameters determined using 2 calorimetric test (0% and 70% slag)
  - Prediction without re-fitting of binders with 0%, 30%, 50% and 70% of slag
Early age mechanical model
General approach for early age modeling

- **Mechanical model needed**
  - Prediction of induced stresses using a rheological model
  - Prediction of crack and damage state using a damage model
    (not presented in this presentation)
  - Adaptation to hardening concrete
**Rheological model**

**Visco-elastic creep model**

\[ \eta = \eta^0 Cc \]

- **Elastic level**
- **Viscoelastic level**
- **Non linear viscous level**

**Modification vitesse de fluage par consolidation**

- **C-S-H**
- **C-S-H Inter layer**
- **Non viscous phase**

**Unified approach for creep and shrinkage**

- **shrinkage**: strain induced by the hydric pressure transmission to solid skeleton
- **Pickett’s effect**: supplementary shrinkage induced by a better transmission of hydric pressure in the direction of the external load
Chemo-mechanical couplings
Numerical adaptation of mechanical model

- Incremental formulation of behavior laws
- Updating of internal variables with hydration development (decrease of damage and consolidation)

Variation of mechanical properties

Variation laws according to hydration degree
⇒ « Usual » properties : Rc, Rt, E

Other properties :
- Fracture energy
- Steel-concrete bond
Application to nuclear waste storage structures
Construction stages

- **Simulation of casting**
  - Block 8m diameter and 5 m long
  - Cast in 1 day
  - A layer of 1m is cast every 5 hours

- **2 cases for boundary condition in the red surface**
  - Convection (block in an empty tunnel)
  - Insulated face (block in contact with bentonite)
Temperature reaches 60°C
Maximal temperature similar in both cases but cooling rate different
⇒ What would be the differences in terms of cracking behavior?
Comparison during heating phase
Stress and damage fields (at the instant of maximal temperature)

Case 1 (convection on 2 faces)
⇒ Low stresses in the tunnel (due to bloc expansion)
⇒ Convective surface in tension with micro-cracking

Case 2 (convection on 1 face)
⇒ Higher stresses in tunnel (higher expansion of the bloc)
⇒ Micro-cracks on tunnel and on “cold” surface of the bloc
Comparison during cooling phase
Damage and crack pattern 40 days after casting

Case 1 (convection on 2 faces)
⇒ Crack at core of the bloc

Case 2 (convection on 1 face)
⇒ Only micro-cracks in the bloc

Comparison
Same mechanical hypothesis on the 2 cases
Differences induced by the thermal boundary conditions

Why the prejudicial case for thermic is not prejudicial for mechanics?
Case 1: Convection on both surfaces

- **Simulation of Case 1**
  - Convection (block in an empty tunnel)
  - Block 8m diameter and 5 m long
  - A layer of 1m is cast every 5 hours

![Diagram of tunnel and casting](image)
Case 1: Convection on both surfaces

- 1 day after casting of the first layer

Concreting phasing

⇒ First layers exhibit higher temperature than the last casted

⇒ Cooling on the surface of the 1st layer: lower stress
Case 1: Convection on both surfaces

- 4 days after casting of the first layer

Heating phase: gradient between core and surface

⇒ Compression at core

⇒ Tension on surface
Case 1: Convection on both surfaces

- 7 days after casting of the first layer

**Instant of the temperature maximum**

⇒ Thermal gradient between core and surface: micro-cracks in surface
⇒ Beginning of cooling: core stress is going to decrease
Case 1: Convection on both surfaces

- 18 days after casting of the first layer

Cooling phase: inversion of stress profile

⇒ Compression in surface (which was colder than core at 7 days)

⇒ Tension at core (maximal value where temperature reached maximum)
Case 1: Convection on both surfaces

- 36 days after casting of the first layer

Cooling phase

⇒ Tensile stress at core reaches tensile strength

⇒ Crack at core (which will propagate)
Case 1: Convection on both surfaces

- 40 days after casting of the first layer

Cooling phase

⇒ Rapid propagation of crack

⇒ Stress tends to zero in a large part of the section
Case 2: Convection on 1 surface only

- Simulation of Case 2
  - Insulation on left surface
  - Block 8m diameter and 5 m long
  - A layer of 1m is cast every 5 hours

![Diagram of tunnel and casting process]
Case 2: Convection on 1 surface only

- 4 days after casting of the first layer

Heating phase: gradient between core and surface

⇒ Compression at core

⇒ Tension on convective surface
Case 2: Convection on 1 surface only

- 9 days after casting of the first layer

Instant of the temperature maximum

⇒ Thermal gradient between core and surface: micro-cracks in surface

⇒ Beginning of cooling: compressive stress is going to decrease
Case 2: Convection on 1 surface only

- 14 days after casting of the first layer

Cooling phase: inversion of stress profile

⇒ Compression in surface (which was colder than core at 7 days)

⇒ On the left face, Tmax but low cooling rate: low “return” of stress

⇒ At core, higher cooling rate and amplitude: tensile stress
Case 2: Convection on 1 surface only

- 42 days after casting of the first layer

Cooling phase: low cooling rate

⇒ Lower stresses reached (than the one observed in case 1)
⇒ No crack was observed
Conclusion
Hydration model for composed binder

- Kinetic strongly coupled with T/W balance equations
- Interaction between clinker and additions
- Stoichiometry of slag-CSH function of CH content at each time step

Mechanical simulation

- Localized crack for the convective case only
- Crack at cooling linked with the cooling rate and amplitude at core

---

CMS Workshop “Cracking of massive concrete structures”
Cachan, 17 March 2015
References


Modelling the mechanical behavior at early-age: influence of the boundary conditions at the structure scale and multiscale estimation of ageing properties

Tulio HONORIO$^{1,2}$; Benoit BARY$^1$; Farid BENBOUDJEMA$^2$
$^1$CEA, DEN, DPC, SECR, Laboratoire d'Etude du Comportement des Bétons et des Argiles, F-91191 Gif-sur-Yvette, France
$^2$LMT (ENS Cachan, CNRS, Université Paris Saclay) 94235 Cachan, France
Concrete at early-age

- Properties evolving at early age (ageing)
- Phenomena taking place at different space and time scales:
  - Solidification
  - Creep
  - Shrinkage
  - Mismatch of properties of matrix and inclusions
  - Heterogenous distribution of stress
  - Internal restraint
  - Environmental conditions
  - External restraint

[Richardson 2004]
Different strategies

- **bottom-up** and **top-down**
- **phenomenological** and **mechanistic** approaches

Accounting for the ITZ and mortar additional porosity

Estimation of reactant and products volume fractions

Mechanistic determination of the kinetics of hydration

**Mesocale**

- Influence of the thermal boundary conditions
- Influence of the restraint conditions
- Analysis by means of a phenomenological approach
- Identification of the zones damaging and cracking
Thermo-chemo-chemical analysis

A phenomenological approach at the structure level
Chemo-thermal problem

- Heat balance
  \[ \dot{T}(x, t) = D \nabla^2 T(x, t) + Q \]
  \[ \begin{align*}
  T(x, 0) &= T_0 \\
  \lambda \nabla T(x, t) \cdot n - k [T(x, t) - T_a] &= q_i(t)
  \end{align*} \quad \forall x \in \Omega_c \quad \forall x \in \partial \Omega_i \]

- Non-homogeneous PDE
  ... with non-homogeneous BC

- Hydration
  \[ \dot{\alpha} = A(t) \cdot \exp[-Ea/T] \]

- Boundary conditions
  \[ q_s - q_c - q_r - q_v = 0 \]
  - Heat conducted into concrete
  - Re-radiation by concrete
  - Heat loss by convection
  - Radiation absorbed
Analytical solutions

Why?

- Elucidates the role of the BC in the chemo-thermal problem
- Validates and allows some extrapolations from the numerical results

\[ l_h = \sqrt{\frac{D}{A(\xi)}} \exp \left[ -\frac{E_a}{R T} \right] \]
Analytical solutions

After some hypothesis and simplifications...

1D solution in a semi-infinite domain non-homogeneous PDE with non-homogeneous BC:

\[ T(x, t) \approx T_1(x, t) + T_2(x, t) + T_3(\xi, x, t) \]

\[
T_1(x, t) = T_0 \left( 1 - \text{erfc} \left[ \frac{x}{\sqrt{4Dt}} \right] + \exp \left[ \frac{k}{D} (kt + x) \right] \text{erfc} \left[ \frac{2kt + x}{\sqrt{4Dt}} \right] \right)
\]

\[
T_2(x, t) = (T_a - \frac{q_s}{k}) \left( \text{erfc} \left[ \frac{x}{\sqrt{4Dt}} \right] - \exp \left[ \frac{k}{D} (kt + x) \right] \text{erfc} \left[ \frac{2kt + x}{\sqrt{4Dt}} \right] \right)
\]

Temperature of concrete at placement

Ambient temperature

Variable flux on boundaries (solar flux)

Reradiation and Convection equivalent exchange coeff.

[Honorio et al. 2014a]
Solar flux

- Convection and reradiaiton
- $T_a$ is kept constant.

- Profiles of temperatures at different times

- Gradient of temperature

- Evolution of the temperatures at different distances from the surface

full lines: no solar flux; dashed lines: constant solar flux
FEM analysis

- Goal: Determine concreting temperatures
- Asymmetric thermal loading induced by solar flux
- Test different T scenarios
  - Precooling?

**Solar flux**

![Solar flux graph](image)

**Validation**

![Validation graph](image)

~ 200k FE in total
~ 100k FE for the wall
**Ambient temperature**

- **Maximum $T$ to prevent DEF problems** $T_{adm}=70^\circ C$
- **Maximum temperature reached within the structure** varies almost linearly with $T_a$

Set of temperatures

---

[Honorio et al. 2014a,b]
Concreting temperatures

\[ T(x, t) \approx T_1(x, t) + T_2(x, t) + T_3(\xi, x, t) \]

\[ T_1(x, t) = T_0 \text{ (…)} \]

\[ T_2(x, t) = \left( T_a - \frac{q_s}{k} \right) \text{ (…)} \]

\[ T_{\text{max}} = c_1 T_0 + c_2 T_a + c_3 \]

Fitting parameters

<p>| | |</p>
<table>
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<tbody>
<tr>
<td></td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>0.359</td>
</tr>
<tr>
<td>°C</td>
<td>34.1</td>
</tr>
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</table>

\[ \Delta T_{\text{ad}} = 46.62 \, ^\circ\text{C} \]

\[ R^2 = 0.81 \]
Mechanical model

\[ \varepsilon_{in} = \varepsilon_{au} + \varepsilon_{th} + \varepsilon_{cr} \]

**Rheological model**

\[
\tau_{bc}^i \dot{\varepsilon}_{bc} + \left( \tau_{bc}^i \frac{k_{bc}^i(\xi)}{k_{bc}^i(\xi) + 1} \right) \dot{\varepsilon}_{bc} = \frac{\ddot{\sigma}}{k_{bc}^i(\xi)}
\]

\[
\begin{align*}
\tau_{bc}^i (\xi) &= k_{bc}^i - \infty \frac{0.473}{2.081 - 1.608 \xi} \\
\tau_{bc}^i &= \frac{1}{k_{bc}^i(\xi)}
\end{align*}
\]

- Exp. 7 days
- Model 7 days
- Exp. 14 days
- Model 14 days
- Exp. 2 days
- Model 2 days

[Honorio et al., under review]
**Cracking index**

- CI and Probability of cracking as a function of the CI:

\[
CI = \max_{\Omega} \left( \frac{\sigma_{ii}(t)}{f_t(t)} \right)_+ 
\]

\[
P(CI) = 100 \times \left[ 1 - \exp \left( - \left( \frac{1}{CI/0.92} \right)^{-4.29} \right) \right] 
\]

The CI obtained from the simulation must be inferior to 54% so that \( P(CI) \leq 5\% \)

Other criteria existing \( \Rightarrow \) B. Craeye (70%); Fairbairn (100%)

**[Honorio et al. under review]**

**Damage model**

- Isotropic damage variable \( D \)

\[
\sigma = (1 - D)\bar{\sigma} 
\]

- Equivalent strain

\[
\hat{\varepsilon} = \sqrt{\langle \varepsilon_e + \beta \varepsilon_{bc} \rangle_+} \quad : \langle \varepsilon_e + \beta \varepsilon_{bc} \rangle_+ 
\]

- Coupling between damage and creep

**MODELLING THE MECHANICAL BEHAVIOR AT EARLY-AGE | T. Honorio et al.**
Thermal conditions: Cracking Index

Aug (oscillating)  Aug (constant)  Nov (oscillating)

First (maximum) eigenstress according to the 3 thermal boundary conditions

\[ t = 15.08 \text{ days} \]

[Honorio et al. under review]
Coupling between creep and damage

August temperatures; \( t = 15.08 \) days

\[ \beta = 0 \quad \beta = 0.05 \quad \beta = 0.1 \quad \beta = 0.2 \]

[Honorio et al. under review]
Thermal conditions: Damage and Crack opening

Aug (oscillating)

\[ \beta = 0.1 \]

Damage →

Crack opening

Nov (oscillating)

\[ \beta = 0.1 \]

Damage →

Crack opening

[Mattalah et al. 2009]
Conclusions

• Phenomenological approaches:
  • It works!
  • *Ad hoc* character: difficult to extrapolate to other scenarios of interest
  • “not very well defined” parameter $\beta$
    • Small variations of $\beta$ can lead to different damage patterns

• Mechanistic approaches to understand the underlying phenomena
  • Justify and improve phenomenological
Multiscale estimation of ageing properties
Concrete at early-age

- Properties evolving at early age (ageing)
- Phenomena taking place at different space and time scales:
  - Solidification
  - Creep
  - Shrinkage
  - Mismatch of properties of matrix and inclusions
  - ITZ
  - Environmental conditions
  - Heterogenous distribution of stress
  - External restraint
  - Internal restraint
  - Reinforced concrete structure

[Richardson 2004]
Hydration kinetics

Goals
- Determine the kinetics from the main driving mechanisms
- Estimate the evolution of volume fraction

Approach
- 2 mechanisms governing hydration:
  - Boundary nucleation and space-filling growth (BNG)
  - Diffusion controlled growth (DCG)

[Honorio et al. 2014c; Honorio et al. Submitted]
Microstructure representation

Repartition of products

[Honorio et al. 2014d]
Solutions in elasticity

Mori-Tanaka

- C-S-H HD
- Pores capillaires
- CH, gypsum or aluminates
- Pores des C-S-H
- C-S-H LD
- ITZ

Generalized Self-Consistent

- Mortar
- Paste
- ITZ

[Honorio et al. 2014d]

[Honorio, Tanaka, 1973]

[Christensen, Lo 1979]
Ageing linear viscoelasticity

Volterra Integral operator:
→ Correspondance principle in a ring \((f; +, °)\)
\[(f \circ g)(t, \tau) \equiv \int_{t'=-\infty}^{t} f(t, t') \, d\tau' \, g(t', \tau)\]

[Volterra 1887; Maghous et al. 2003; Sanahuja, 2013]

- Volterra Integral operator:
  - Correspondance principle in a ring \((f; +, °)\)
  \[(f \circ g)(t, \tau) \equiv \int_{t'=-\infty}^{t} f(t, t') \, d\tau' \, g(t', \tau)\]

C-S-H HD

C-S-H LD

- C-S-H : viscoelastic behavior
  - Intrinsically ageing?
  - Solidification → ageing behavior

Mori-Tanaka

Generalized Self-Consistent
Numerical homogeneization

Goals:
- Investigate the influence of the aggregates
- Get local information
- Study more complex microstructures

Elasticité

Matrix: cube (120x120x120 mm$^3$)
- Number of inclusions: 872
  - Equivalent diameters: 8-18 mm

Ageing linear viscoelasticity

Dispersion on stresses within the inclusions

[Honorio et al. 2014d]
Conclusions

Different strategies to investigate the behavior at early-age

Mechanistic approach:
- Some phenomena still need to be better understood (hot point!)
- Some tools still to be developed

Perspectives
- Contribution to the study of the ageing viscoelastic behavior
  - Influence of the ageing mechanisms at the paste level
  - Influence of the aggregates (shape, PSD, vol. fraction)
  - Mismatch of matrix-inclusions properties
  - Thermal effects
References


Honorio, T.; Bary, B.; Benboudjema, F. Factors affecting the thermo-chemo-mechanical behavior of massive concrete structures at early-age: a numerical study. (under review) [HONrev]


Acknowledgments

This present work has been performed as part of the project on disposal of LILW-SL that is carried out by ONDRAF/NIRAS, the Belgian Agency for Radioactive Waste and enriched Fissile Materials.
Is there more risk of cracking with today’s cements than with yesterday’s cements?

Laurent IZORET

1ATILH (Technical Association of French Cement Industry)
• **Short reminder:** By itself, cement shrinkage does not implies accidental cracking…

  - **Influencing factors and trends of variation**
    - Clinker mineralogy
    - Fineness of grinding
    - Nature of main constituent other than clinker
    - Alcalies

  - **Shrinkage evolution since 25 years**
    - Since 1986 (1) : ATILH Round Robin test (cement)
    - Since 1986 (2) : Cement database (manufacturer)
    - Depuis 2006 (mesures tous les ans)
Cement shrinkage

Influencing factors and trend of variations
**Shrinkage measurement**

- CEN mortar; w/c = 0.5
- Prisms 4x4x16 cm
- Curing: 20°C/50% H.R.
- R3, 7, 14, 28, .. days

**What do we measure?**

![Diagram of shrinkage measurement process]

1. **Setting**
2. **Thermal shrinkage**
3. **Self-dessication**
4. **Le Chatelier contract**
5. **Drying**
6. **Plastic**

![Graph showing time vs. shrinkage](image-url)
From Venuat (1968)
Evolution of risk of cracking from cements

From Cement database (cement manufacturer)

\[ y = 13.534x + 509 \]
\[ R^2 = 0.4393 \]

\[ y = 14.604x + 512.29 \]
\[ R^2 = 0.4749 \]
Tentative modelisation

Shrinkage =
- 0.012aC3S(t)*[%C3S] -
- 0.07aC2S(t)*[%C2S]
- 2.256aC3A(t)*[%C3A]
+ 0.859aC4AF(t)*[%C4AF]
From Venuat (1968)

Role of alcalies on shrinkage
From Venuat (1968)
From Cement database (cement manufacturer)

- Role of Slag on shrinkage vs time
- Slag content in cement vs shrinkage at 28d

Graphs showing the evolution of risk of cracking from cements.
First conclusion

At 28 days, shrinkage remains influenced by the following parameters:

• Cement C3A content and C3S content in a lesser extend
• Fineness of gringing
• Alcalis concentration, e.g. Na2O
• Nature of main constituent other than clinker (Slag requiring the most attention…)
• Range from 400 to 800 μm/m

Are theses characteristics constant over time?
Cement shrinkage

Is there an evolutionary trend?
Is there a correlation with manufacturing conditions?
Alternative Fuels in cement Kilns (F):
Evolutionary trend

- **Liquids**
  - Water-solvants
  - Used oils

- **Solids**
  - Farines animales
  - Old tyres
  - Solid Wastes (papers, cartons, plastics, ...)

- **Trend**
  - Increasing 1986-2001
  - Stability since 2001
ATILH Data Base Cement Annual Round Robin Test

- Approx 250 Labs over the world
- Between 180 to 220 validated results per year
- 1 Cement type per year

→ Flat trend
→ No relationship to alternative fuels
→ Fluctuations due to cement types
Second conclusion

From one database type:

- 28 days shrinkage ranges from 400 to 800 µm/m depending more on cement type than alternative fuels substitution rate in the cement kilns.

- Early age shrinkage (3d) remains limited between 100 to 200 µm/m with low scattering.

- **Clue**: no trend since 25 years over several cement types
Since 1986 (2): cement data base

From a second database type (cement manufacturer):

- About 8 000 measurements over 25 years

- Two scales of time and two frequencies of report
  - For a given cement type, between 2 to 6 measurements/ Y.
  - 1986-2010 (report frequency every 5 years)
  - 2006-2012 (report frequency every year)
Cement Data Base (Cement Manufacturers)

- Period 986 – 2011
- Report every 5 years
- CEM I 52.5R & N

Standard shrinkage CEM I 52.5 R&N

---

Evolution of risk of cracking from cements | L. Izoret
Cement Data Base
(Cement Manufacturers)

- Period 986 – 2011
- Report every 5 years
- CEM I 52.5R & N

Standard shrinkage CEM I 52.5 R&N
Cement Data Base (Cement Manufacturers)

- Period 1986 – 2011
- Report every 5 years
- CEM I 52.5R
Cement Data Base (Cement Manufacturers)

- Period 1986 – 2011
- Report every 5 years
- CEM I 52.5R

**Standard shrinkage CEM I 52.5 N vs time**

![Graph showing standard shrinkage CEM I 52.5 N vs time](image)
Cement Data Base (Cement Manufacturers)

- Period 1986 – 2011
- Report every 5 years
- CEM I 52.5 SR

CEM I 52.5 PM-ES (SR) over 25 years

EVOLUTION OF RISK OF CRACKING FROM CEMENTS | L. Izoret
Cement Data Base
(Cement Manufacturers)

- Period 2006-2012
- Report every year
- CEM I 52.5N

Standard shrinkage CEM I 52.5N vs time
Cement Data Base (Cement Manufacturers)

- Period 2006-2012
- Report every year
- CEM III/A or B

Standard shrinkage CEM III/A or B vs time
Cement Data Base
(Cement Manufacturers)

- Period 2006-2012
- Report every year
- CEM II/A-S 42.5

Standard shrinkage CEM II/A-S 42.5 vs time
Cement Data Base (Cement Manufacturers)

- Period 2006-2013
- Report every year
- CEM I 52.5R
Third and final conclusion

From a second database type (cement manufacturer):

- All cement types are not equivalent
  - by mean of grinding fineness
  - by mean of the nature of main constituent
    - Low clinker content cements can vary depending on Slag, Fly ash and Limestone
    - Fluctuation in shrinkage may come from main constituent other than clinker e.g. slag

- Flat trend from shrinkage evolution over 25 years
- The risk of cracking due to cement contribution hasn’t increased in 25 years
References

- Venuat M., “Influence du ciment sur le retrait hydraulique après prise”. Publication technique du Centre d’étude et de recherches sur les liants hydrauliques (CERILH), n° 189, mai 1968. (in French)