Thermo-mechanical couplings of concrete at early age: from material to structure

Laetitia D'ALOIA
CETU - Centre d'études des tunnels
Bron, France

"From concrete nanoscale to structure " Celebrating Gilles Chanvillard's memory

July 5-6 2016

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

Overview

- Back to researches carried out during the 90's at ENTPE
    - → **my PhD [1993 -1998] supervised by Gilles Chanvillard**

- Some additional researches and studies performed at LCPC (now IFSTTAR) and CETU a few years later

- *Good agreement between lessons learned from past experience and the strategic and practical direction set by Lafarge Holcim today*

Training by research ENTPE [1993-1998]

- Each year, about 10 young engineers have the opportunity to do a PhD
- Gilles? A human and a professional story. The feeling to be part of a great "family" that never won't leave you … indifferent
  - Gilles, a genius teacher!
    - He was just back from Canada and was teacher/researcher at ENTPE
    - He was really keen on concrete and he fascinated all students with his energy, passion and contagious laugh
    - A that time, everything had to be done regarding concrete research at ENTPE
  - I liked construction materials
  - I was dreaming to teach and to do researches
  - I was fascinated by the well-known play:

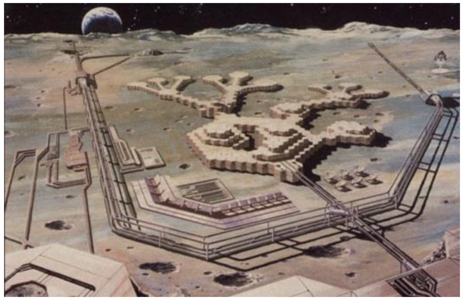
    « Les Palmes de monsieur Schutz » …

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

The short story of the thesis topic

- At the beginning, I'd like to do a PhD on lunar concrete!
  (I guess, I used to watch too much TV …)
- Gilles: "C'est génial !"
- A few days later, he had already found documents on lunar concrete: the committee report ACI SP 125 « Lunar concrete » (1991)
- But, we had to land on earth and we understood that we had to behave as "politician" and to find a more consensual subject
- A collaboration was launched between LCPC and ENTPE about concrete strength estimation at early age. In the long term, the main goal was to implement a specific module in the FE program CESAR-LCPC
- Jean Michel TORRENTI supervised the research theme on the mechanical behavior of concrete at LCPC
- And thus began my PhD with all the support I could never have imagined …



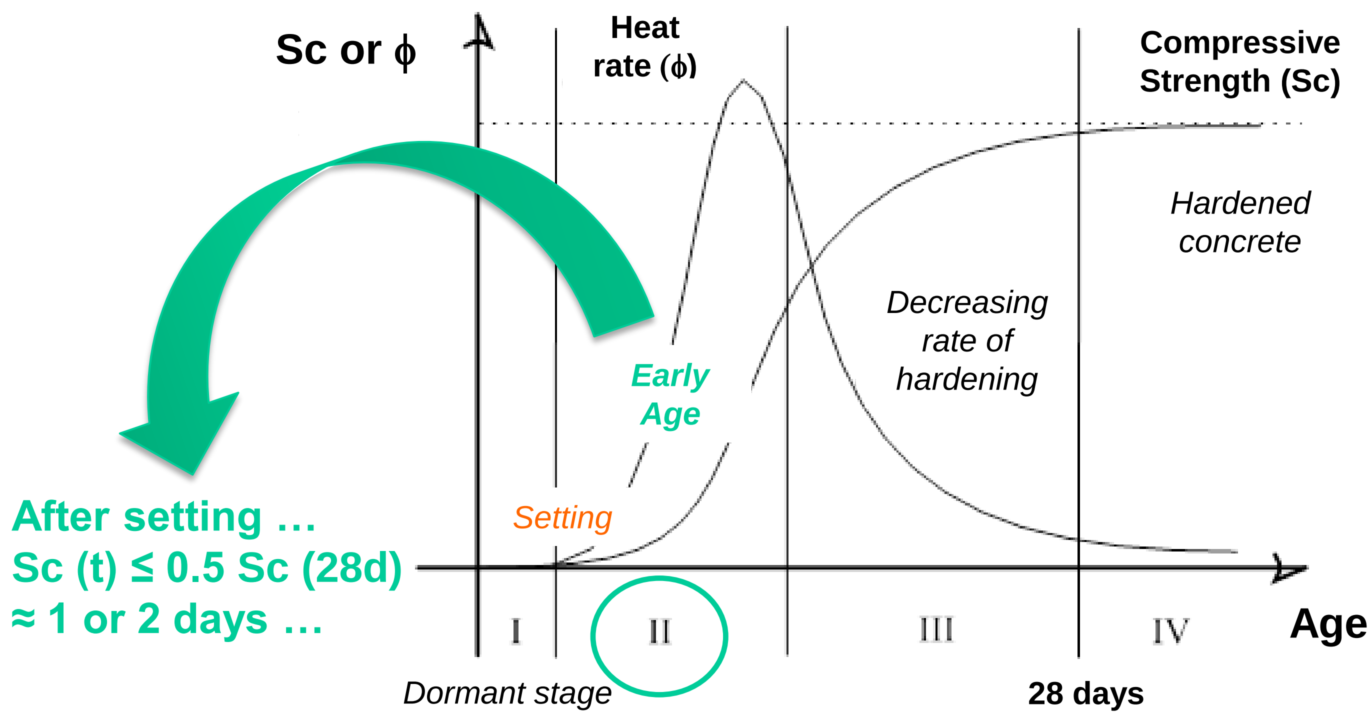
Lunar Base, Shimizu

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Concrete at Early Age

Early Age of concrete?



Cement hydration ≈ Chemical reactions between cement and water
→ concrete hardening and temperature increase within structures

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

Early age main issues

- **Concrete strength estimation:**
  - Small standard samples don't reproduce the actual in-place concrete temperatures → don't represent the actual concrete strength development
    - *How to accurately estimate the in-place concrete strength to ensure formwork removal, early and safe pre-stressing?*

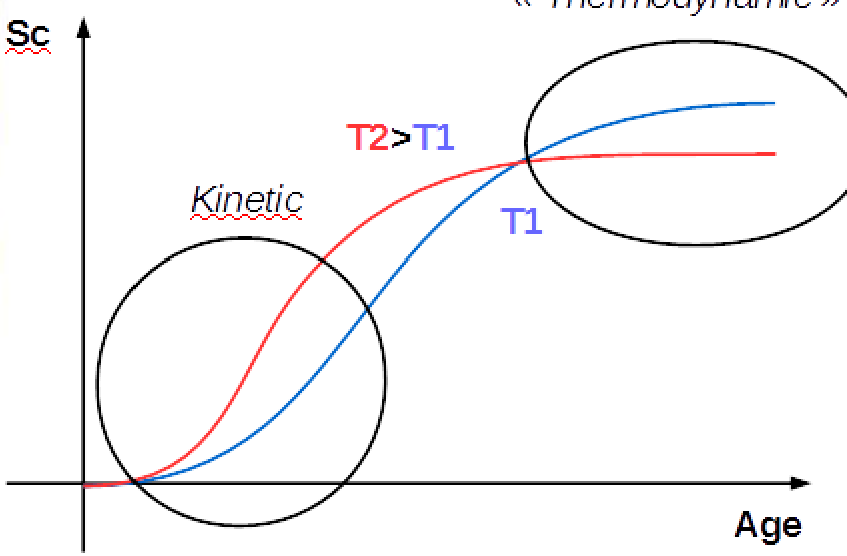
⇨ *Optimization of the rate of building by accounting for thermal effects!*

- **Temperature and thermal gradients estimation:**
  - Competition between heat released within massive concrete structures and its diffusion to the ambience
    - *How to limit the induced thermal stress to avoid thermal cracking?*
    - *How to avoid high temperature at early age to prevent chemical disorders from appearing?*

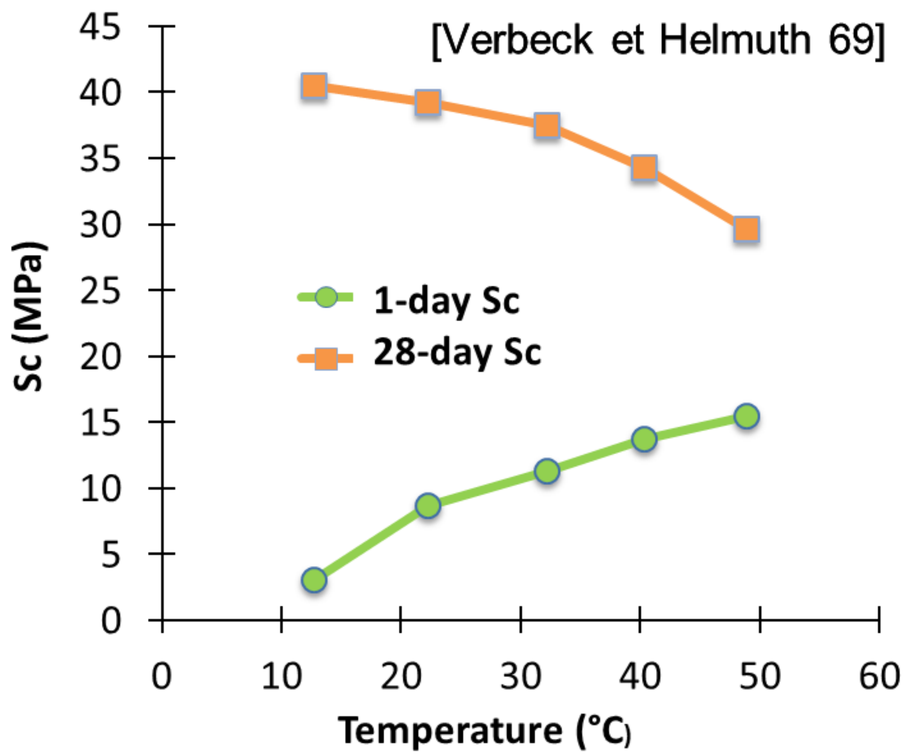
⇨ *Improvement of durability by limiting thermal gradients and high temperature at early age!*

Influence of temperature on concrete strength

Isothermal curing:



[Byfors 80] [Laplante 93] [D'Aloia 93]…



- **Kinetic** effect at early age: ↗ T ⟶ ↗ rate of hardening
- **"Thermodynamic"** effect at later ages: ↗ T ⟶ ↘ Sc

“Maturity” and the concept of “Equivalent Age”

- **“Maturity”**:
  - *"Concrete of the same mix at the same maturity has approximately the same strength whatever combination of time and temperature go to make up that maturity”* [Nurse 49] and [Saul 51] [Nikänen 56]

$$M\left(t, H(T)\right) = \int_0^t K\left(T(\tau)\right) d\tau = M\left(t_{eq}, T_{ref}\right) = K\left(T_{ref}\right) t_{eq}$$

$M\left(t, H(T)\right)$: maturity at age *t* for a given temperature history $H(T)$

$H(T)$: temperature history : $T(\tau), \tau \in [0, t]$

$K(T)$: rate constant,

$T(t)$: temperature, K

- ***“Equivalent Age”:***
  - *“The Equivalent Age represents the age of curing at the reference temperature that would result in the same strength as would result from curing at other temperatures”* [Rastrup 54] [Mac Intosh 56] [Freiesleben Hansen and Pedersen 77]

$$t_{eq} = \int_0^t \frac{K\left(T(\tau)\right)}{K\left(T_{ref}\right)} d\tau$$

$M\left(t_{eq}, T_{ref}\right)$: maturity at age for the reference temperature , T_{ref}

t_{eq} : equivalent age at the reference temperature T_{ref} usually 20° C (293K).

$$t_{eq\ FHP} = \exp\left(-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{réf}}\right)\right) t$$

Influence of temperature

- **“Kinetic”** effect:
  - Arrhenius’ law (“simple” chemical reaction! → approximation in the case of cement hydration) → rate constant expression K(T) and reaction rate (v):

$$K(T) = A\exp\left(-\frac{Ea}{RT}\right)$$

$$v = \frac{\partial \alpha}{\partial t} = K(T)g(\alpha)$$

T : absolute temperature, K
R : gas constant, 8.314 J/mol K
Ea : «Apparent» Activation Energy, J/mol

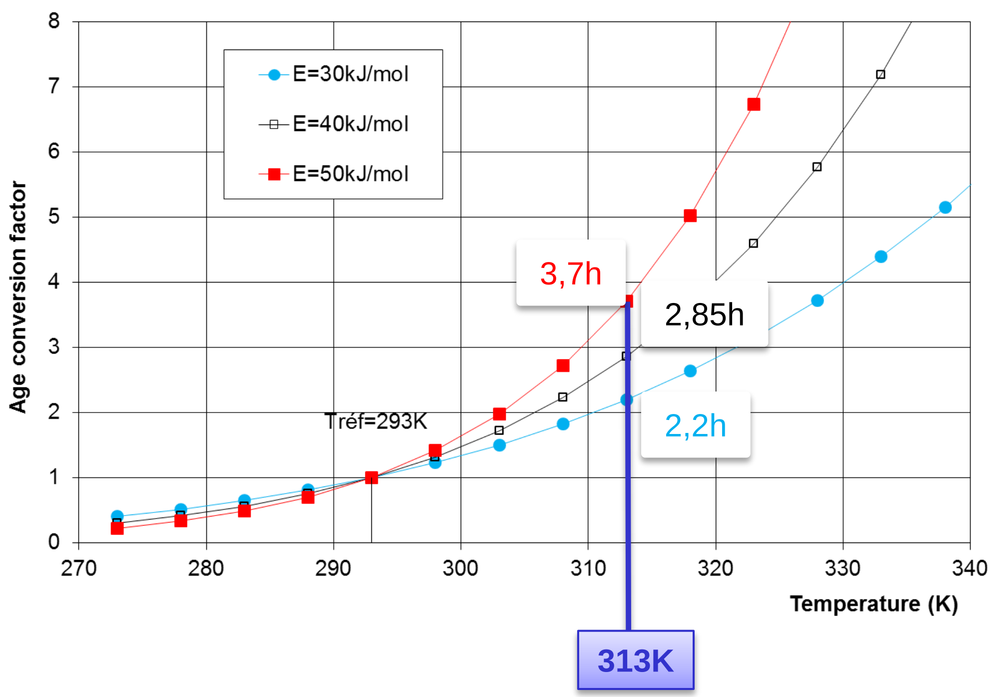
v : hydration rate
α : hydration degree (Sc/Sc_{final}. or q/q_{final}.)
g(.) : function of α

→

- Ea is the **“apparent” activation energy of concrete**
- Ea can depend on **mix design parameters** (type of cement, w/c, mineral additions, …) and physical variables: **T and α**
- Ea has to be **experimentally** determined!

γ and Ea

For isothermal curing
"*Age conversion factor*": $\gamma = \frac{t_{eq}}{t} = \frac{K(T)}{K(T_{ref})} \exp\left(-\frac{Ea}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$



[D'Aloia 98]

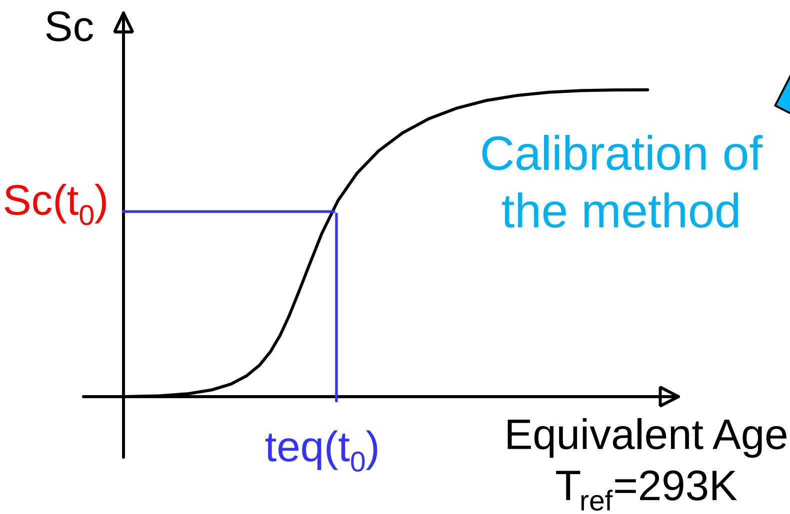
Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
Ministère de l'Environnement, de l'Énergie et de la Mer

Ea represents the **sensitivity of the hydration kinetic** to a change in temperature

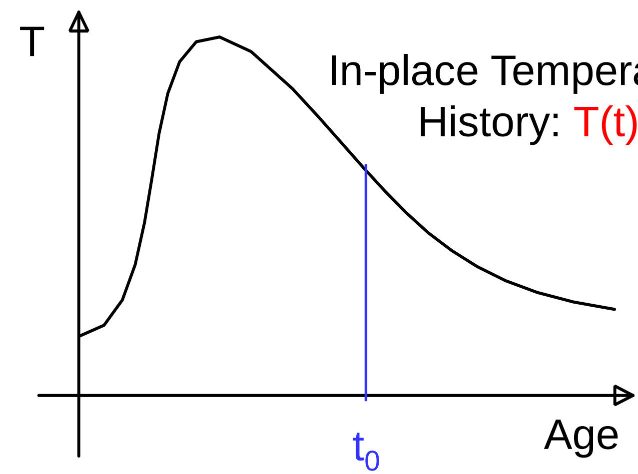
Concrete strength estimation at early age

- Application of the **method of "Equivalent age"** to the estimation of in-place concrete strength:

1) "Reference Curve": (Sc, teq) + Ea



Calibration of the method

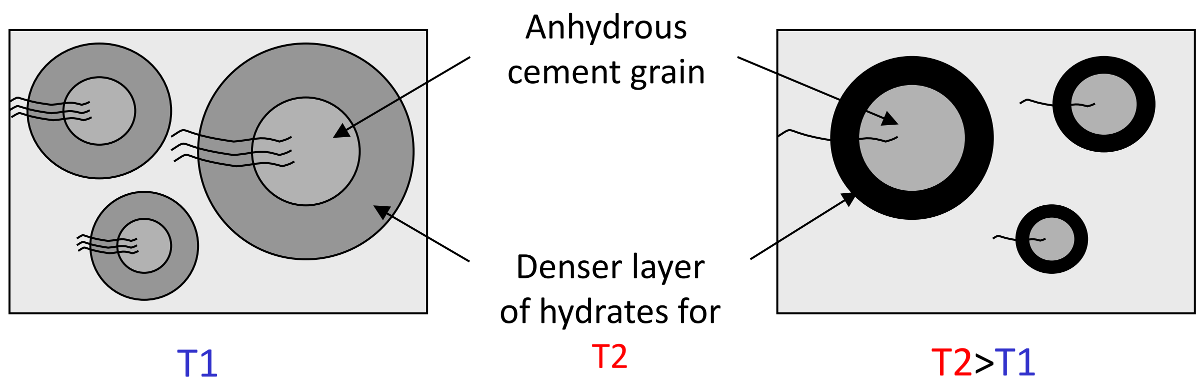


3) $Sc(t_0)$

2) $$teq(t_0) = \int_0^{t0} \exp\left(-\frac{Ea}{R}\left(\frac{1}{T(\tau)} - \frac{1}{T_{ref}}\right)\right) d\tau$$

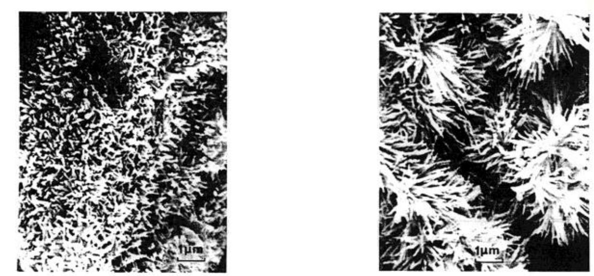
Influence of temperature

- **“Thermodynamic”** effect:



- A different and more heterogeneous hydrates arrangement and a lower final cement hydration degree at higher isothermal curing temperature

[Verbeck and Helmuth 69]
[Regourd et Gautier 80]
[Kjellsen 90] [Van Breugel 91]



C-S-H formation at 20 and 80° C

- A differential thermal expansion of constituents and a setting at high temperature

[Kjellsen 90] [Laplante 93]

⇨ *Precautionary measure for precast concrete!*

Long term compressive strength modelling

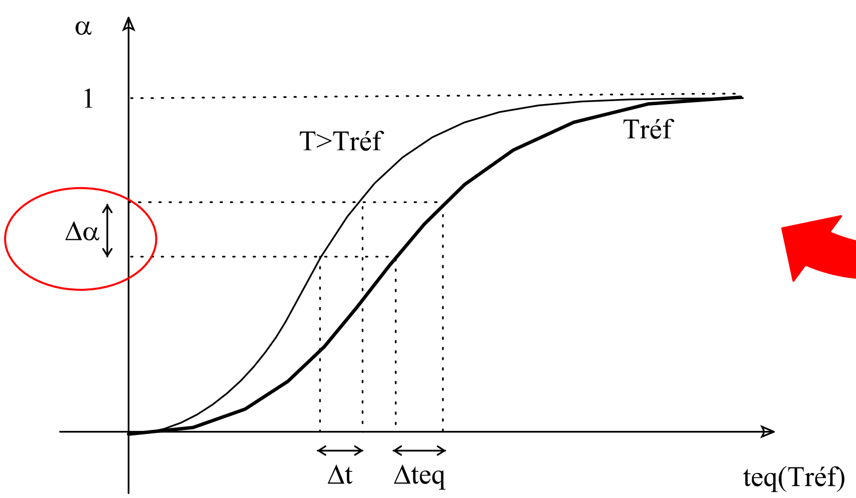
- **First idea:** to improve concrete strength estimation at early age by accounting for the “thermodynamic” influence of T on Sc_{28d}

Isothermal curing: T → Sc28d

$$Sc_{28d}(T) = Sc_{28d}(293K)(1 - k(T - 293))$$

- On the basis of a literature review (fitting on experimental results): $k = 0.01$
- The method of equivalent age is applied to the estimation of α

$$Sc(t, H(T)) = \sum_t Sc_{28d}(T)\Delta\alpha(\Delta t, T) = \sum_t Sc_{28d}(T)\Delta\alpha(\Delta t_{eq}(T_{réf}))$$



The method was improved ! BUT …

- Modeling was not really satisfactory …
- Mathematical model of interpolation
- Setting time
- Proper determination of Ea?

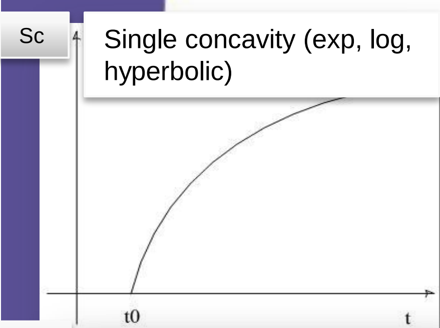
[Chanvillard D’Aloia 1997]

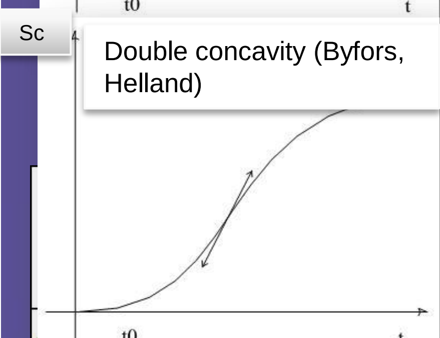
Ea determination

Type of test and method?

Mechanical or Calorimetric tests?

- **Determination of Ea: obtained by comparing at least two different thermal conditions (two tests)**
  - **Mechanical tests**:
    - Main drawbacks:
      - discontinuity of experimental results and use a model of interpolation
      - strong influence of T on Sc_{28d}
      - test procedure …
    - Main advantages:
      - same property as that you are supposed to estimate!
      - setting time …



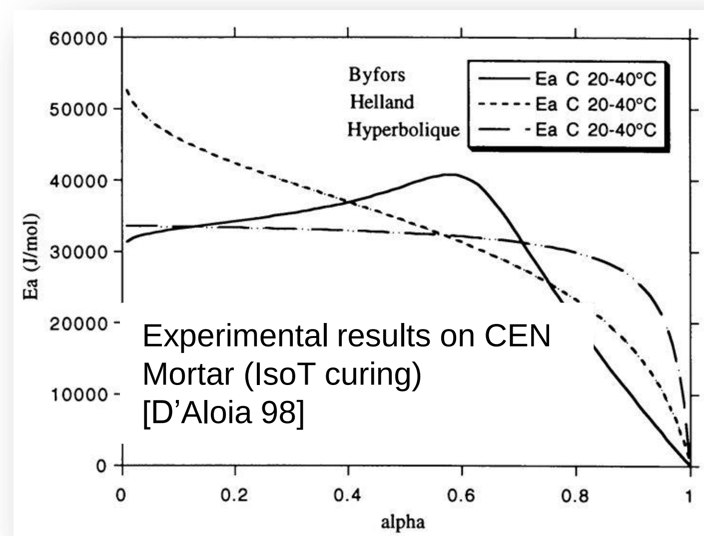


[Byfors 80] $$Sc = \frac{at^b}{1+ct^d}$$

[Helland] … $$Sc = Sc_\infty \exp\left(-\left(\frac{b}{t}\right)^c\right)$$

[McIntosh 56] [Carino 82]… $$Sc = \frac{t-t_0}{\frac{1}{A}+\frac{t-t_0}{Sc_\infty}}$$

with t_0 setting time



Strong dependence of Ea on the mathematical model of interpolation

de l'Environnement,
de l'Énergie
et de la Mer

Mechanical or Calorimetric tests?

- **Determination of Ea: obtained by comparing at least two different thermal conditions (two tests)**
  - **Calorimetric tests** (2 different thermal conditions):
    - Main advantages:
      - continuous measurement
      - easier test procedure
      - no significant influence of T on q_{∞} or q_{28d}
    - Main drawback:
      - additional step of mechanical validation
  - **3 types** of calorimetric tests:
    - Adiabatic (“CERILH” calorimeters)
    - **Semi adiabatic** (LCPC-QAB calorimeters for concrete and Langavant calorimeters for mortar (NF EN 196-9))
    - Isothermal …

➡ The choice of the type of test could depend on expected temperatures

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

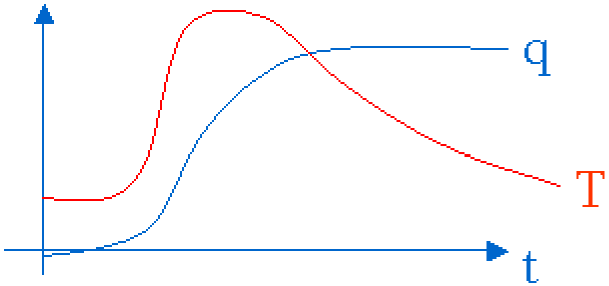
Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Calorimetric tests

- **Semi-adiabatic calorimetry:** thermal exchanges with the ambience → **LCPC-QAB calorimeters** ("quasi-adiabatic") for concrete and **Langavant** (NF EN 196-9)) for mortar
  - Thermal losses are calculated :
    - Calibration of QAB calorimeters :
      - coefficients of thermal losses have to be experimentally determined: a et b
      - specific heat of the calorimeter: µ
    - A control calorimeter is required (inert specimen) $\theta(t)=T(t)-T_{control}(t)$
    - The ambience needs to be regulated $T_{ambient}\approx T(t_0)\approx T_{control}$

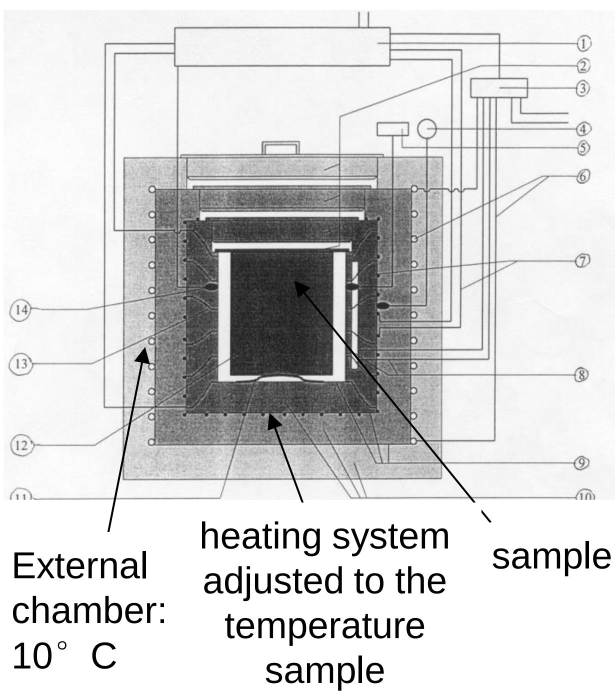
Calculation of hydration heat

$$q(t)=\frac{C}{m_c}(\theta(t)-\theta_0)+P(t)$$
$$=\frac{C}{m_c}(\theta(t)-\theta_0)+\frac{1}{m_c}\int_0^t\left(a\theta(\tau)+b\theta^2(\tau)\right)d\tau$$



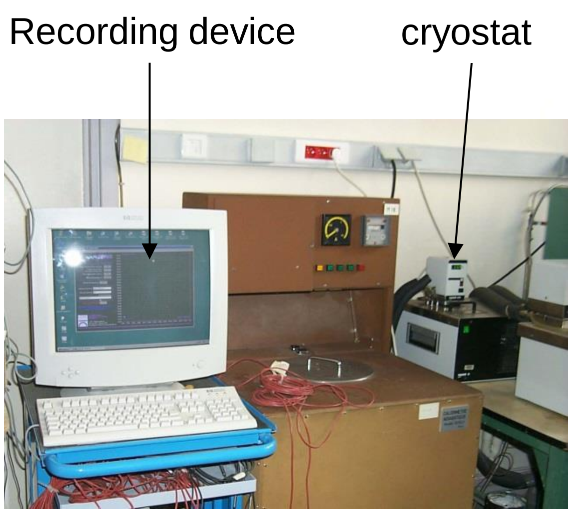
Calorimetric tests

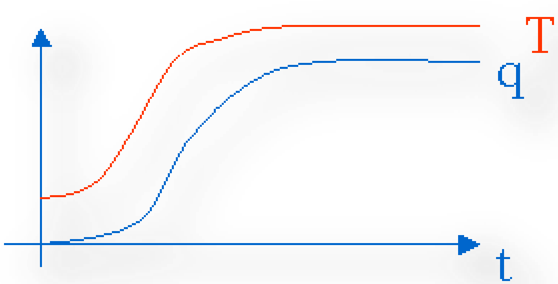
- **Adiabatic calorimetry:** no thermal exchange with the ambience OR the ambient temperature is adjusted to the core temperature of the sample → **"CERILH" calorimeters** for concrete
  - Calibration of calorimeters :
    - Specific heat capacity of the calorimeter: μ
  - The ambience doesn't need to be regulated



Calculation of hydration heat

$$q(t) = \frac{C}{m_c}\left(T(t) - T_0\right)$$





Ea Estimation?

- Ea is determined on the basis of two calorimetric tests initiated at two different temperatures
- Two analyzing methods:
  - The **"superposition method"**
  - The **"speed method"**

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

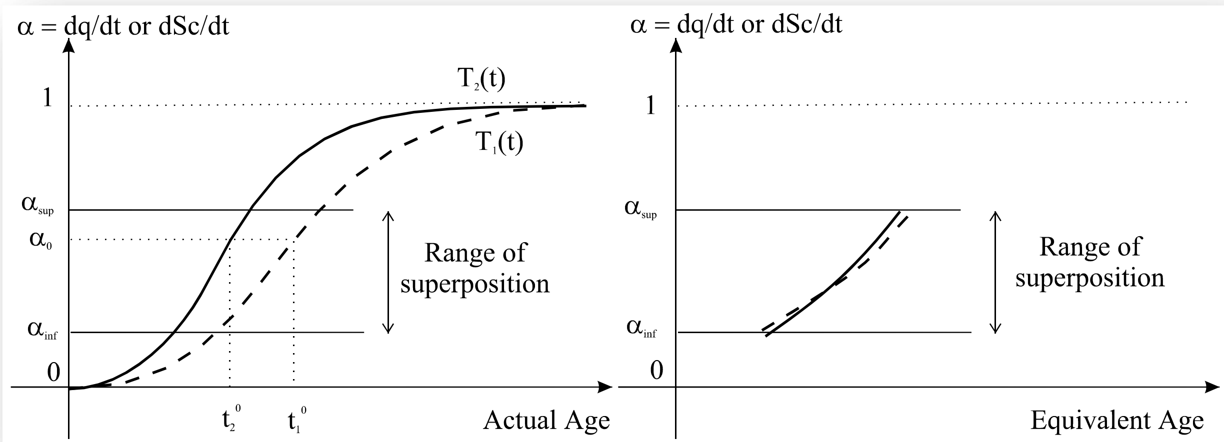
Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Ea Estimation?

- Ea is determined on the basis of two calorimetric tests initiated at two different temperatures
- Two analyzing methods:
  - The **"superposition method"** → for calorimetric or strength tests

a least squares criterion:

$$\min_{Ea}\left(\sum_{\alpha_i \in [\alpha_{\inf}, \alpha_{\sup}]} \left|t_{eq\,1i} - t_{eq\,2i}\right|^2\right)$$



$$t_{eq\,1i} - t_{eq\,2i} = \int_0^{t_{1i}} \exp\left(-\frac{E_a}{R}\left(\frac{1}{T_1(\tau)} - \frac{1}{T_{ref}}\right)\right)d\tau - \int_0^{t_{2i}} \exp\left(-\frac{E_a}{R}\left(\frac{1}{T_2(\tau)} - \frac{1}{T_{ref}}\right)\right)d\tau$$

→ Several distinct Ea-values can be determined.
The concept of "doublet" or "triplet" (2 or 3 Ea-values) was proposed by the CTG ItalCementi. Each Ea-value can be adopted depending on the extent of hydration [Roussel 1996]

Ministère de l'Environnement, de l'Énergie et de la Mer

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

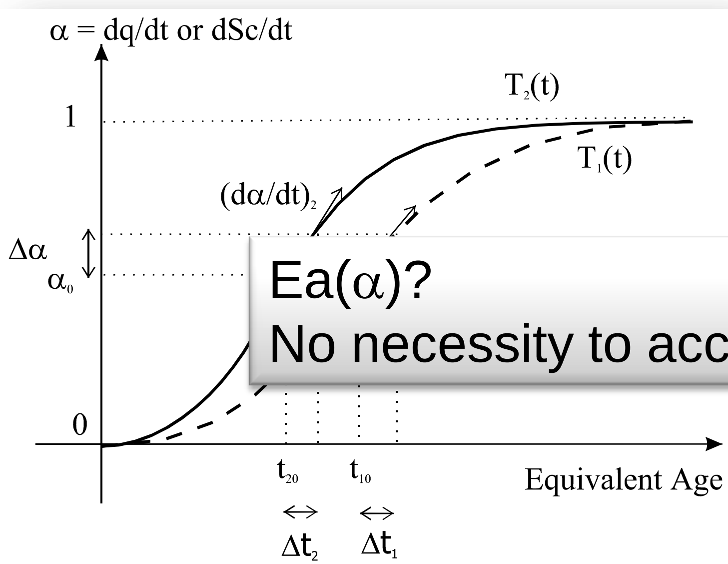
Ea Estimation?

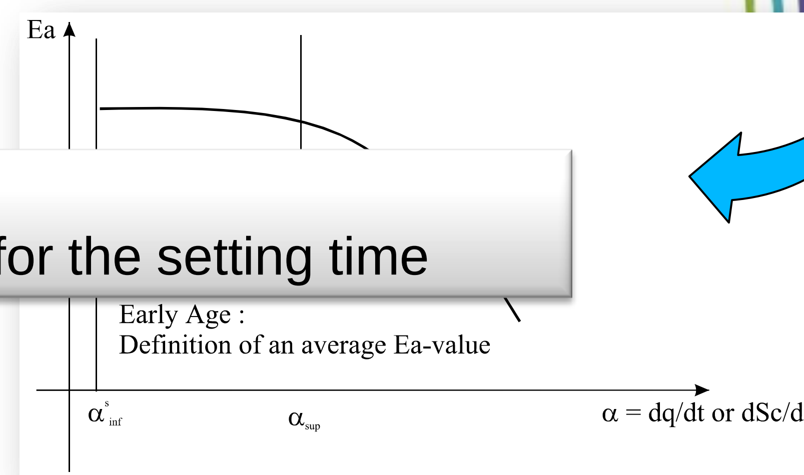
- Ea is determined on the basis of two calorimetric tests initiated at two different temperatures
- Two analyzing methods:
  - The **"speed method"**

$$\frac{d\alpha}{dt} = f(\alpha)\exp\left(-\frac{E_a}{RT}\right)$$

$$\left(\frac{d\alpha}{dt}\right)_1(\alpha_0) = \left(\frac{d\alpha}{dt}\right)_2(\alpha_0)\exp\left(-\frac{E_a}{R}\left(\frac{1}{T_1(\alpha_0)} - \frac{1}{T_2(\alpha_0)}\right)\right)$$

$$E_a(\alpha_0) = -\frac{R}{\frac{1}{T_1(\alpha_0)} - \frac{1}{T_2(\alpha_0)}}\ln\frac{\left(\frac{d\alpha}{dt}\right)_1(\alpha_0)}{\left(\frac{d\alpha}{dt}\right)_2(\alpha_0)}$$





Ea(α)?
No necessity to account for the setting time

Experimental campaigns

Experimental campaigns

- Most of these campaigns have been performed in collaboration with the CTG - Italcementi Group (Pierre LAPLANTE, Sylvie LECRUX, Vincent WALLER) and with the CETE de Lyon (Sylvie ARNAUD) → French National Project CALIBE (Quality of concrete)
  - Calorimetric and mechanical campaigns
  - Wide range of initial temperatures: [10, 37° C]
  - Concrete and equivalent mortars
  - Different types of cement: CEMI, CEMII, CEMIII (different C3A contents – mineral additions and SP - …) → Sensitivity of the setting time and Ea to temperature?
  - The test procedure for semi-adiabatic calorimetry has been more detailed to prevent results from being distorted by experimental errors
  - …

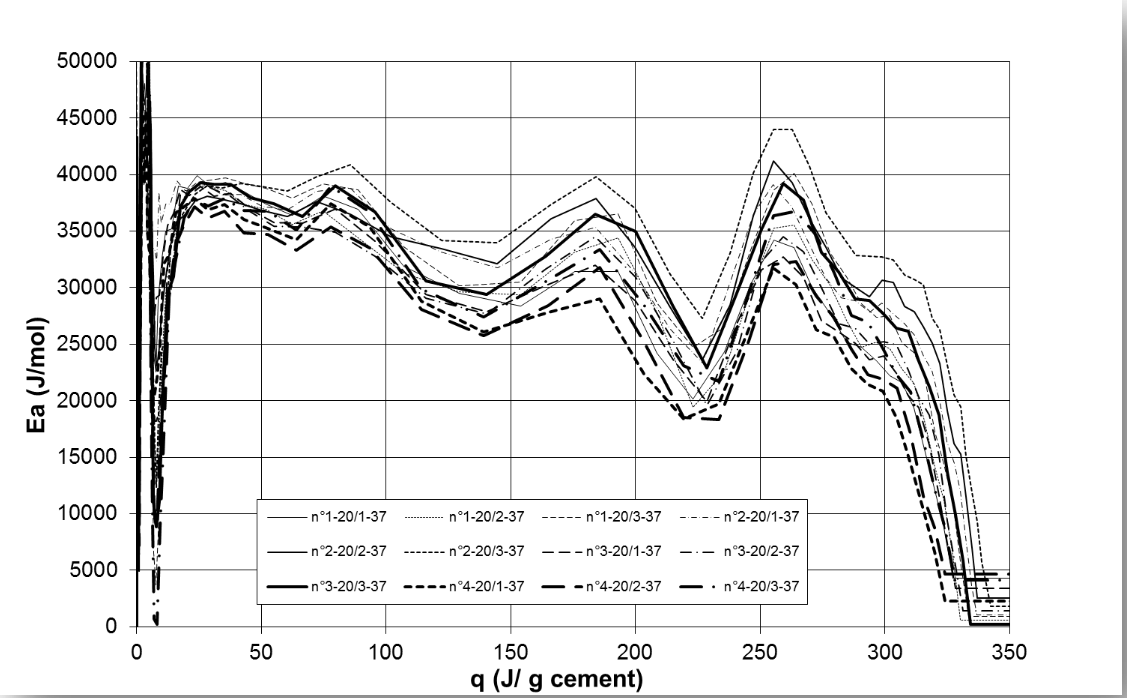
- ***Some lessons drawn from experimental campaigns …***

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Repeatability

- **Langavant (mortar) – CEMI 52,5:**
  - 4 tests at Tini=20° C and 3 tests at Tini=37° C
  - Ea has been calculated from 10 to 25 and 40% of hydration **(Discrepancies were limited: Ea → 5kJ/Mol)**



Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

Numerical modeling

Numerical simulations

Hydration heat modeling

- **The idea at the basis of the modeling:**
  - To simulate heat rates under adiabatic conditions for different initial temperatures to determine Ea
  - « Apparent » activation energy Ea → **multi phasic approach: Ea_i for each i-phase**
  - **Main assumption:** independent hydration rates of cement phases (≈24h!) → cement hydration rate
  - Themal coupling are accounted for **(Arhenius' Law)**
  - Microstructural effects are neglected (fineness, particle size distribution, …)

[D'Aloia Chanvillard 2002]

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

Hydration heat modeling

- **Data:**
  - **Cement:** mineral composition (Bogue's formula) including SO_3
  - For **each cement phase**: →

$$Ea^i, \left(\frac{dq^i}{dt}\right)_{T_{réf}} (q^i), q^i_{max}$$

  - **Existing data**: [Kishi Maekawa et al. 95] ... [Parrott et Killoh 84] ...
  - **Kinetic model** and fitting of parameters

Avrami-Erofeev, [Banfill 94] ("ciments fondus")

$$\alpha^i(t) = 1 - \exp\left(-K_i t^{n_i}\right)$$

n_i, K_i parameters

$20 < Ea^i < 70$ kJ/mol

$K_i > 0$

$2 \leq n_i = n_{i,nucleation.} + n_{i,growth.} \leq 6$

  - Experimental campaign: **calorimetric results**

(%)	CEMI	PMES
C_3S	47.66	53.63
C_2S	24.89	21.83
C_3A	9.52	3.04
C_4AF	7.14	12.31
SO_3	3.55	2.86

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
Ministère de l'Environnement, de l'Énergie et de la Mer

Hydration heat modeling

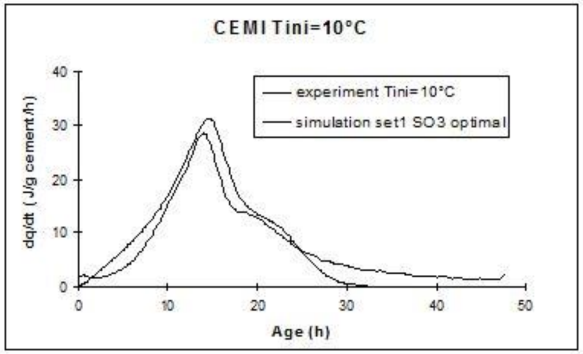
- **Constraints and fitting:**

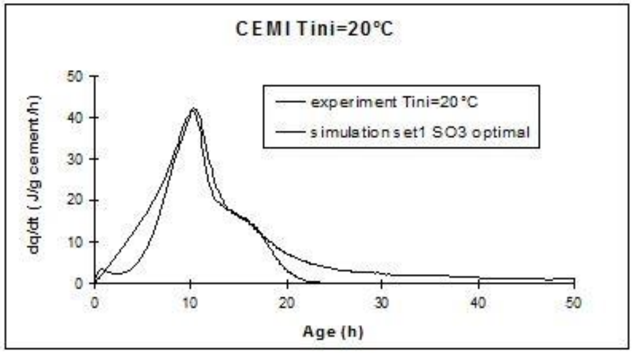
C_3A+SO_3 → Ettringite → monosulfoaluminate

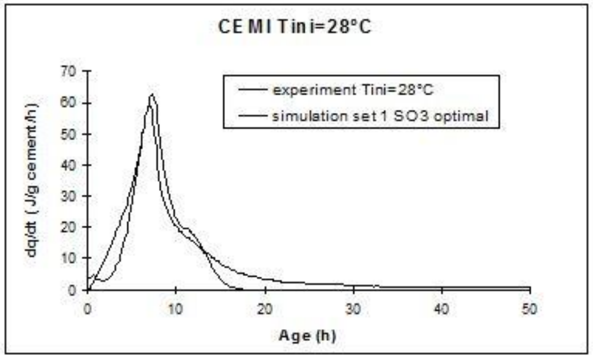
α_0 $\alpha_0 = 0.9$

  - **set 1 and set 2 (C3S and C3A):**
    - Heat rate peak of C3A precedes that of C3S
    - Optimal SO3 content → conversion into monosulfoaluminate is complete when sulphate is exhausted

	C_3S		C_3A → ettringite		ettringite → monosulfoaluminate	
	Set 1	**Set 2**	**Set 1**	**Set 2**	**Set 1**	**Set 2**
$K_i\left(1/t^{ni}\right)$	5.4^{E}-3	5.5^{E}-3	4.7^{E}-4	4.7^{E}-4	4.8^{E}-3	3.5^{E}-3
n_i	2	2	3	3	2	2
q^i_{max} *(J/gC_3S or C_3A)	502	502	1420	1402	1300	1300
Ea^i / R (1/K)	4000	4000	4700	5200	3000	3500

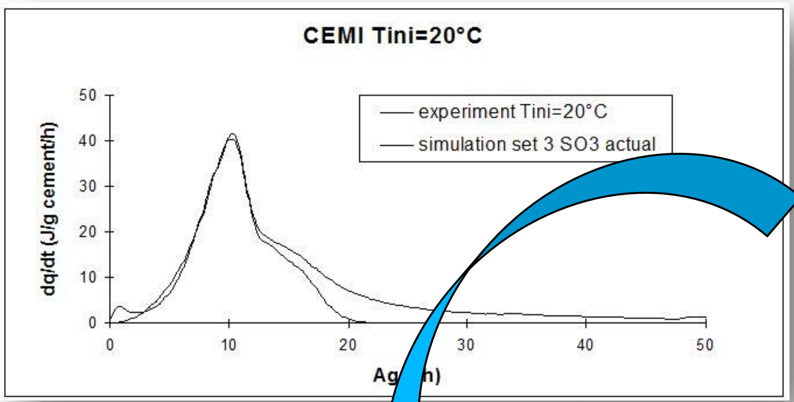


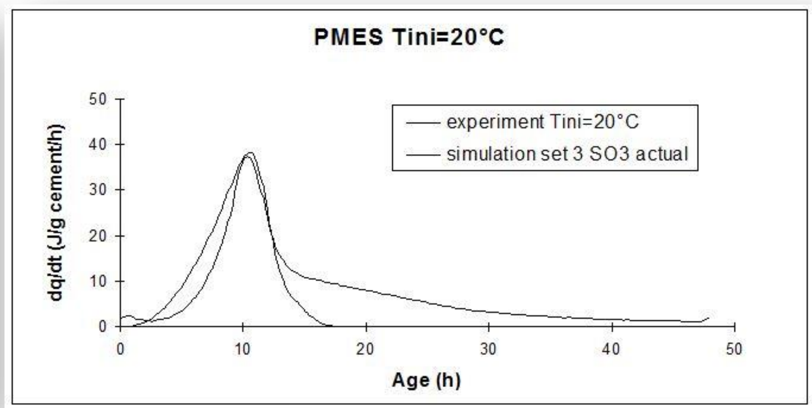




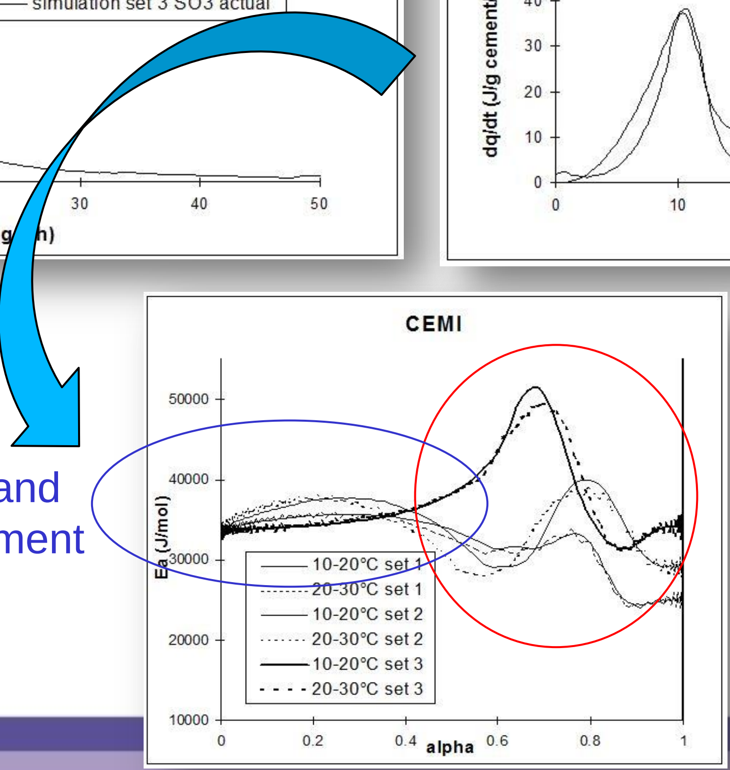
Hydration heat modeling

- **Fitting parameters Set 3:**
  - The first peak of C3A (ettringite formation) closely follows the C3S peak
  - The two C3A reactions are synchronised at a higher degree $\alpha_0 = 0.4$
  - Actual SO3 content





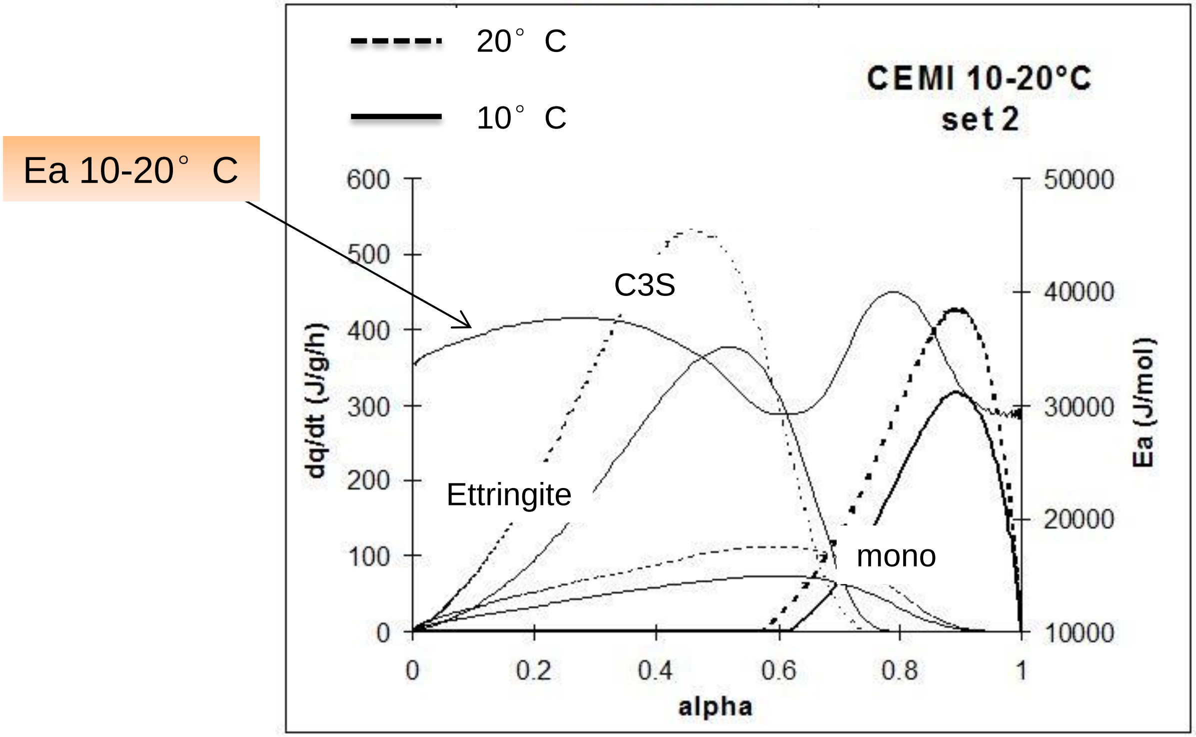
Almost constant and independent of cement (→ C3S)



Great variations

Hydration heat simulations

- **Parallel evolution of EA and heat flow of phases (CEMI – Set2):**

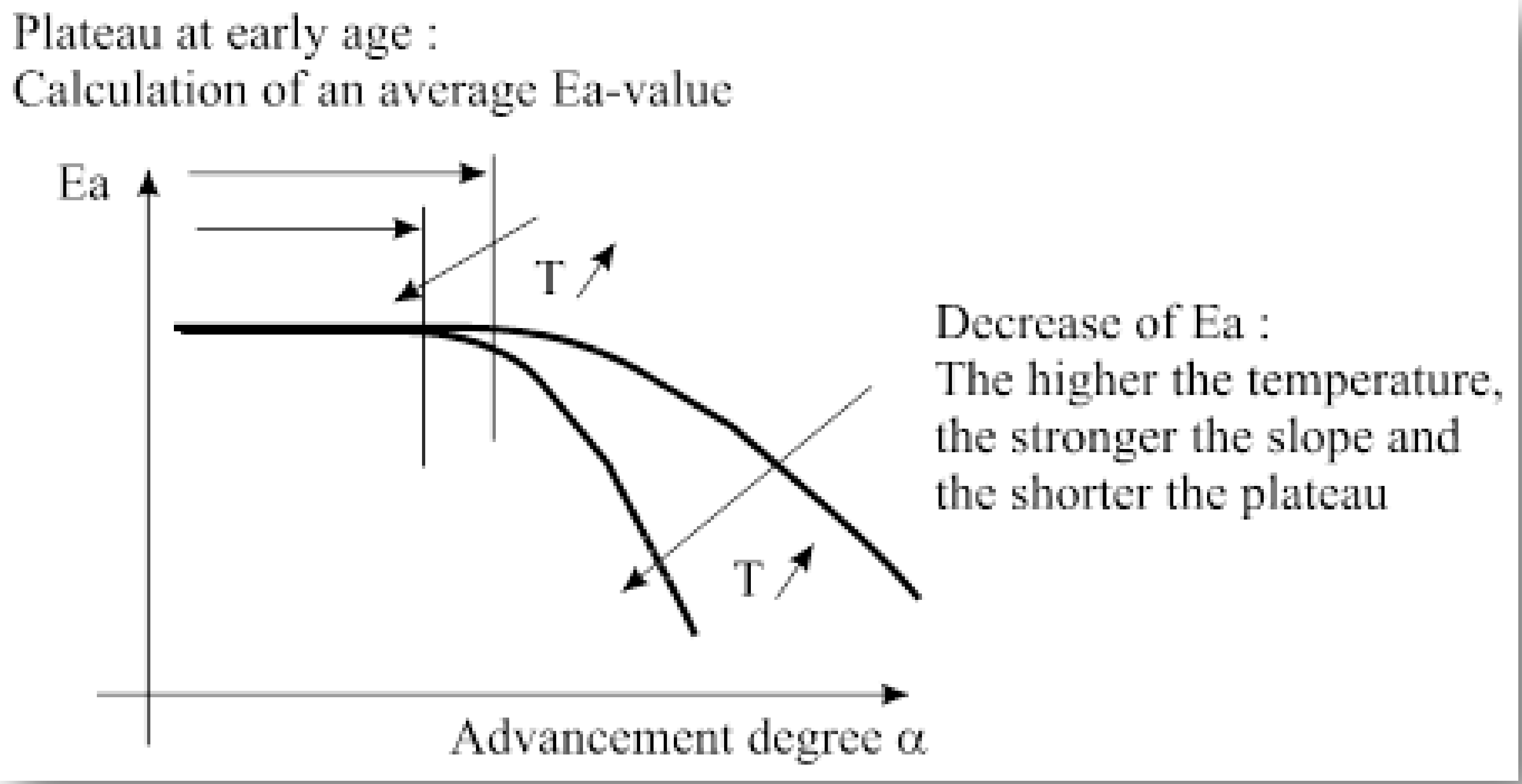


➡ **The simulation program CHAL does emphasize the "apparent" nature and the polymineral characteristic of cement**

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer

General conclusion on Ea



Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

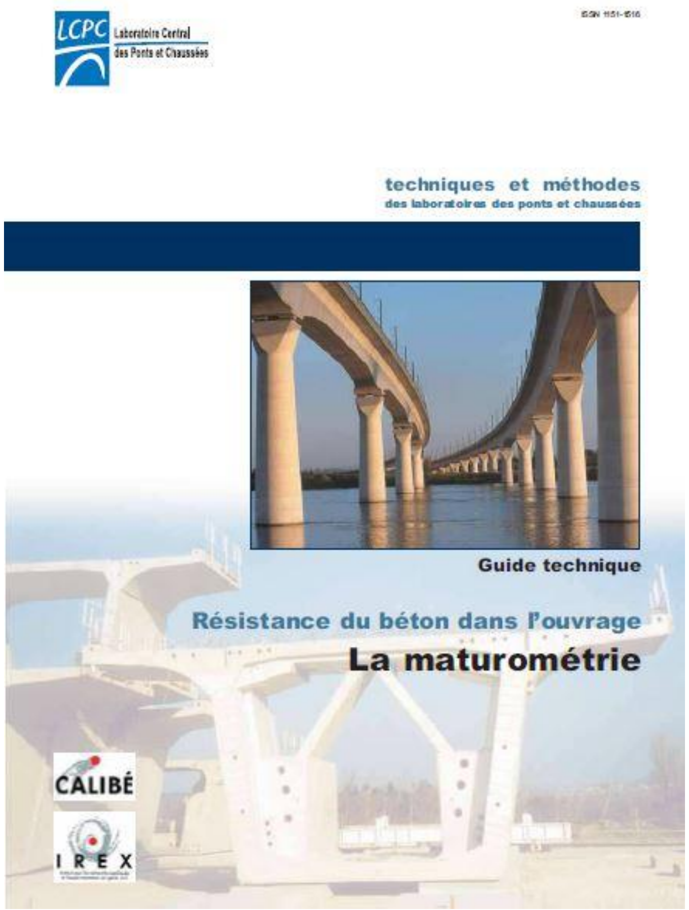
Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Field applications

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Concrete strength estimation



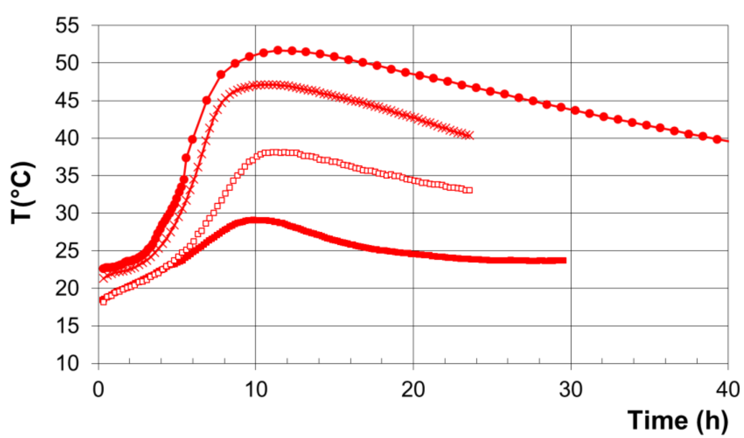
LCPC Recommendations:
“Résistance du béton dans l’ouvrage : La maturométrie”
[Projet National CALIBE, 2003]

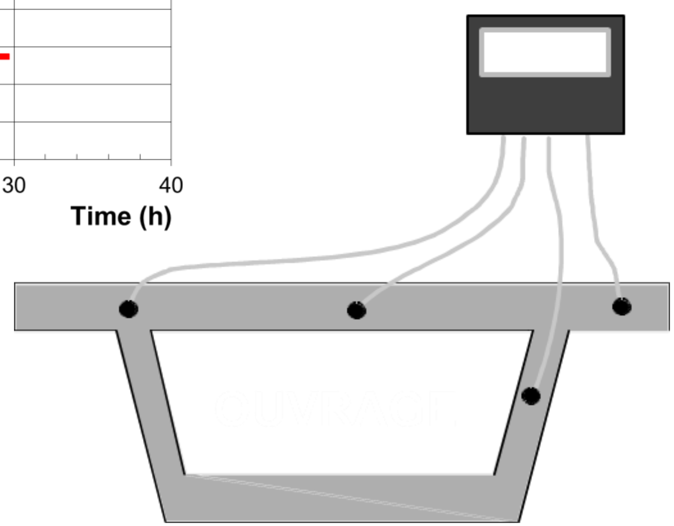
Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

Concrete strength estimation

- **Measurement of in-place concrete temperature** T(t):
  - Recording of in-place temperature measurements
  - Calibration parameters are stored in the device
  - Early age concrete strength can be estimated for each thermal history





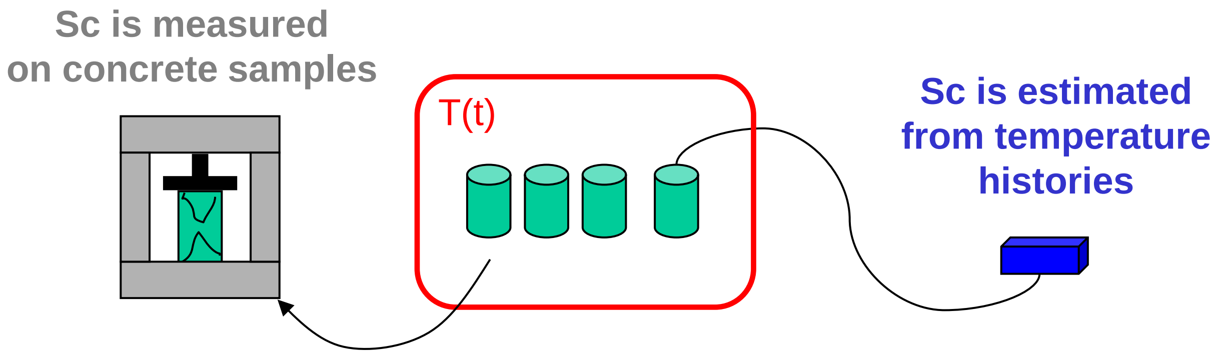
Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE
Ministère de l'Environnement, de l'Énergie et de la Mer

Concrete strength estimation

- **Calibration of the method: calibration curve and Ea**
  - Thermal conditions of calibration similar to those expected on site!

- **Conformity controls**:
  - Comparison between **measurement** and **estimation of Sc**:
    - Concrete samples are submitted to a given thermal treatment
    - Sc is estimated on the basis of measured temperatures
    - Sc is measured on concrete samples
    - 2 types of conformity controls: at the begining and during works

- **Main objectives:**
    - To validate the calibration of the method of equivalent age → **reference curve**
    - To control the regularity of process of concrete production



Concrete strength estimation Field application

- **From the practical point of view :** the superposition method is mostly used on mechanical tests for the calibration of Ea
  - Why? To avoid the additional step of mechanical validation when performing calorimetric tests. Easier tests on site!
  - **Attention should be paid to the calibration procedure!**
- **At an upstream stage (optimization of building phases)** → use of numerical tools. Both the superposition and the speed methods are used for calorimetric tests
  - Easier tests on lab! Several numerical tools …
- *The maturity method or equivalent age method is often used in France (especially in tunnels…). Last tunnel : Saint Béat*

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère de l'Environnement, de l'Énergie et de la Mer

After my PhD

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Later studies at LCPC - CETU

- **Guide-LCPC "Maturométrie"** (National Project CALIBE) (2003)
- **Calorimetric tests procedures** have been improved, data recording and results analysis automatized for both **semi-adiabatic and adiabatic tests**
- **Calorimetric tests and numerical simulations** performed for specific construction sites and with different goals
  - Viaduct of Verrières (→ Millau bridge) – Concrete mix design and **optimization of phasing** …
  - **Durability:** evaluation of maximum temperature at early age (DEF)
  - Application to **Self Compacting Concrete (SCC)**
  - **Comparison between adiabatic and QAB tests** (equivalent mortars and concrete)
  - Accounting for **the setting time** in the determination of Ea
  - Accounting for **evaporation** in the estimation of early age temperature by FE Program
  - Better understanding the **cracking of concrete tunnel lining**

→ **Several phenomena have to be accounted for in case of field application! (autogeneous shrinkage, thermal shrinkage, drying …)**

Later studies at LCPC - CETU

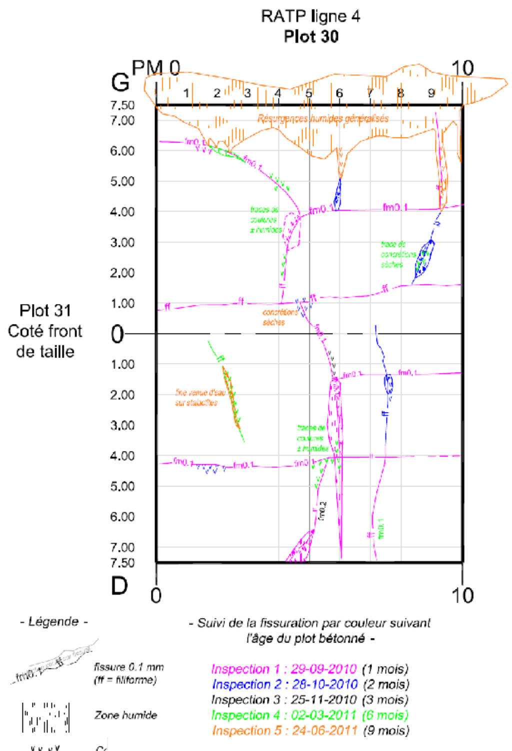
- **Guide-LCPC "Maturométrie"** (National Project CALIBE) (2003)
- **Calorimetric tests procedures** have been improved, data recording and results analysis automatized for both **semi-adiabatic and adiabatic tests**
- **Calorimetric tests and numerical simulations** performed for specific construction sites and with different goals
  - Viaduct of Verrières (→ Millau bridge) – Concrete mix design and **optimization of phasing** …
  - **Durability:** evaluation of maximum temperature at early age (DEF)
  - Application to **Self Compacting Concrete (SCC)**
  - **Comparison between adiabatic and QAB tests** (equivalent mortars and concrete)
  - Accounting for **the setting time** in the determination of Ea
  - Accounting for **evaporation** in the estimation of early age temperature by FE Program
  - Better understanding the **cracking of concrete tunnel lining**

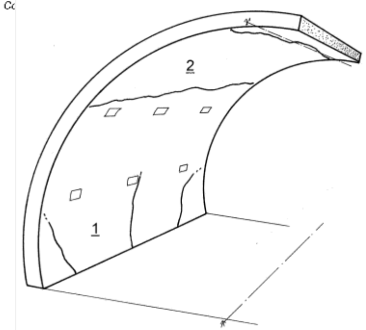
→ **Several phenomena have to be accounted for in case of field application! (autogeneous shrinkage, thermal shrinkage, drying …)**

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer

Other researches
CETU – ENS Cachan



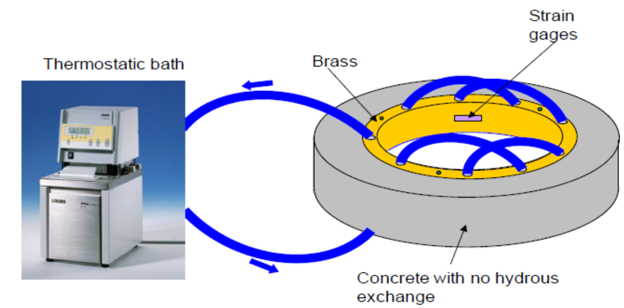


[Briffaut, Benboudjema, D'Aloia 16]

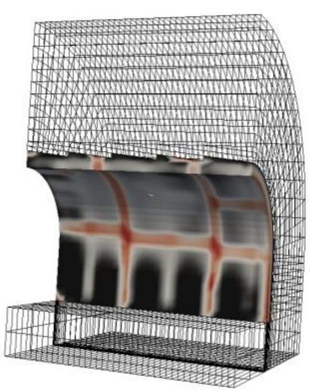
Influence of micro and macro PP and Metallic fibers on the concrete sensitivity to cracking

(Subway M4/RATP → replacement of steel mesh – Thick concrete lining without watertightness)

Thermal – Autogeneous and drying shrinkages

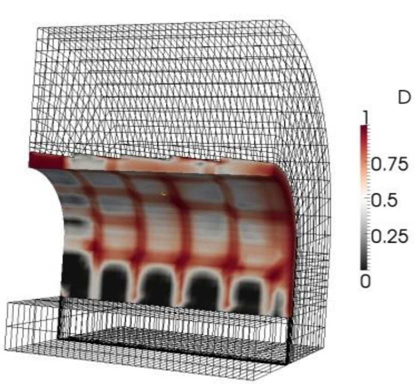


Thermal active ring test



Damage field due to both thermal and autogenous shrinkages after 360 hours (CASTEM)

← including creep



Thank you for you attention
Thank you Gilles!

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

Ministère
de l'Environnement,
de l'Énergie
et de la Mer