The Revision of the French Recommendations for the Prevention of Delayed Ettringite Formation

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Introduction

✓ In France, the first DEF case was diagnosed in 1997 on the Ondes Bridge near Toulouse (on the capbeam of a pier cast in place).

✓ Then, DEF was discovered in other bridges, especially in massive parts cast in place and in contact with water (piers, crossbeams,…)

Ondes Bridge: View in 2005 of the end of the cap beam after treatment in 1995
More recently, DEF was found in the precast prestressed concrete edge beams of 25 bridge decks on a motorway...
Introduction

✓ In order to prevent new disorders in France, LCPC published in 2007 Provisional Recommendations to avoid DEF

These recommendations are now mentioned in the new version of the French standard on concrete
NF EN 206/CN
A remind of the previous recommendations... (2007)
Remind on the preventive approach

The bases of the methodology:

1. To identify the parts of the structure that are likely to develop DEF
2. To choose the category in which each part of the structure falls
3. To characterize the environment
4. To choose the level of prevention
5. To adopt precautions corresponding to the level of prevention
To identify the parts of the structure

✓ The precast products subjected to a heating treatment

✓ The parts of structures that are defined as critical elements

The notion of massive element is not relevant ⇒ example:

Footing with thickness 1.5 m:
C30/37, content 370 kg/m$^3$ of CEM III/A 42,5 N ⇒ $\Delta T = 29^\circ$C

Wall with thickness 0.6 m:
C40/50, content 400 kg/m$^3$ of CEM I 42,5 R ⇒ $\Delta T = 45^\circ$C

Definition of a critical element: Concrete element for which the generated heat is only partially dissipated towards outside and leads to a high rise of the concrete temperature (Thickness is at least greater than 0.25 m)
## Choice of the category

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples of structures (or part of structures)</th>
</tr>
</thead>
</table>
| **Category I**<br>Low or acceptable consequences | - Structures with compressive strength class lower than C16/20  
- Non structural elements inside buildings  
- Easy to replace elements, temporary structures  
- Most of non structural precast products |
| **Category II**<br>Not very tolerable consequences | - Structural elements belonging to most of the buildings and civil engineering structures (including current bridges)  
- Most of structural precast products (including pipes under pressure) |
| **Category III**<br>Unacceptable or quasi-unacceptable consequences | - Nuclear power plants and atmospheric cooling towers  
- Dams, tunnels  
- Exceptional bridges and viaducts  
- Monuments or prestigious buildings  
- Railway sleepers |
# Choice of the exposure class

<table>
<thead>
<tr>
<th>Exposure class</th>
<th>Description of the environment</th>
<th>Informative examples illustrating the choice of the exposure classes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XH1</strong></td>
<td>Dry or moderate humidity</td>
<td>- Parts of concrete structure located inside buildings where the humidity content of the ambient air is low or average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Parts of concrete structure located outside and sheltered from the rain</td>
</tr>
<tr>
<td><strong>XH2</strong></td>
<td>Humidity and drying cycles or High humidity</td>
<td>- Parts of concrete structure located inside buildings where the humidity content of the ambient air is high</td>
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<tr>
<td></td>
<td></td>
<td>- Parts of concrete structure not protected by a coating and subjected to the bad weather, without water stagnation on the surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Parts of concrete structure not protected by a coating and subjected to frequent condensations</td>
</tr>
<tr>
<td><strong>XH3</strong></td>
<td>In durable contact with water:</td>
<td>- Parts of concrete structure submerged permanently in water</td>
</tr>
<tr>
<td></td>
<td>Permanent immersion, water stagnation on the surface, tidal zone</td>
<td>- Elements of marine structures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- A great number of foundations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Parts of concrete structure regularly exposed to sprayed water</td>
</tr>
</tbody>
</table>
### Choice of the level of prevention

**Responsibility of the owner**

<table>
<thead>
<tr>
<th>Category of structure</th>
<th>Exposure class</th>
<th>XH1</th>
<th>XH2</th>
<th>XH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>As</td>
<td>As</td>
<td>As</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>As</td>
<td>Bs</td>
<td>Cs</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>As</td>
<td>Cs</td>
<td>Ds</td>
<td></td>
</tr>
</tbody>
</table>
Principle of prevention (unchanged)

✓ The principle of prevention is essentially based on

✓ 1) the limitation of the concrete heating characterized by \( T_{\text{max}} \) likely to be reached within the structure

✓ 2) In case \( T_{\text{max}} \) can not be respected, then necessity to act on the concrete composition or to practise a performance test adapted to DEF

✓ The recommendations give calculation tools for the concrete heating:

  ✓ simplified method allowing to estimate if the elements are considered to be critical \( \Rightarrow \) alert tool

  ✓ refined study using a software based of the finite element method which takes into account the heat released by the concrete in a specific test (adiabatic test)
Revision of the prevention measures (2017)
New elements since 2007

Context of a wider use of CEM II/A-L & LL (blended portland cement incorporating up to 20 % calcium carbonate) to mitigate carbon footprint…

Two Studies were conducted to assess the efficiency of several additions combined with cement:

1) LNEC Study
   National Laboratory of Civil Engineering at Lisbon, Portugal)

2) FNTP Study (with the help of IFSTTAR)
   French Federation of Public Works Companies
LNEC Study

LNEC conducted a long-term study (3 000 days) on the expansion rate and microstructure of heat-cured concretes with different amounts of mineral additions with the same Portland cement CEM I (clinker C3A = 8%, Cement SO₃ = 2.7%, Cement Na₂Oeq = 1.2%).

The mineral additions tested were:

- fly ash (10, 15, 20 and 30% in mass)
- metakaolin (5, 10, 15 and 20%)
- ground granulated blast-furnace slag (10, 15, 20 and 40%)
- silica fume (5 and 10%)
- limestone filler (10, 15, 20 and 30%)

Main Results: The percentages at which each addition begins to be more effective in inhibiting the expansive reaction are:

- 30% for fly ash
- 20% for metakaolin
- 40% for ground granulated blast-furnace slag
- 10% for silica fume
- Limestone filler increases expansion!
FNTP-Ifsttar Study

FNTP (with Ifsttar): around **20 different concrete mixes were tested** through the French long term DEF performance test protocol

- (CEM I and CEM II/A-LL) produced with the same clinker (C3A = 10%, Cement SO₃ = 3.5%, Cement Na₂Oeq = 0.6%)
- The following mineral additions were selected:
  - ground granulated blast-furnace slag (35, 40, and 60% in mass)
  - fly ash (20 and 30%)
  - metakaolin (20%)
  - silica fume (10%)

Two concrete thermal cycles were taken into account:

- Cycle n₁: Peak threshold 75 °C during 3 days
- Cycle n₂: Peak threshold 85 °C during 3 days

**Main results:**

**With thermal cycle 2 (85 °C):**
- For 40% and 60% of GGBS: expansion below threshold
- For 20% and 30% of fly ash: expansion below threshold

**With thermal cycle 1 (75 °C):**
- For 35% of GGBS: expansion below threshold
- For 20% of fly ash: expansion below threshold
- For 20% of Metakaolin: expansion below threshold
- For 10% of silica fume: expansion below threshold
Main Modifications

No change to categories, exposure classes and prevention levels

No change to the temperature limits:

\[ \text{As} = 85 ^\circ \text{C}, \quad \text{Bs} = 75 ^\circ \text{C}, \quad \text{Cs} = 70 ^\circ \text{C}, \quad \text{Ds} = 65 ^\circ \text{C} \]

Delete condition 6 on references of use for precast products (never applied)

New condition 5 for Level Bs and Cs:

<table>
<thead>
<tr>
<th>Past Recommendations</th>
<th>New Recommendations</th>
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</thead>
<tbody>
<tr>
<td>No use of CEM II-A-L &amp; LL</td>
<td>Use of CEM II-A-L &amp; LL allowed</td>
</tr>
<tr>
<td>GGBS &gt; 20 %</td>
<td>GGBS &gt; 35 %</td>
</tr>
<tr>
<td>Fly ashes &gt; 20 %</td>
<td>Fly ashes &gt; 20 %</td>
</tr>
<tr>
<td>Metakaolin &gt; 20 %</td>
<td>Metakaolin &gt; 20 %</td>
</tr>
<tr>
<td>Silica Fume not allowed</td>
<td>Silica fume allowed with content &gt; 10 %</td>
</tr>
</tbody>
</table>
Main Modifications

For level Ds: Validation by a laboratory expert in DEF has been deleted

Conditions based on concrete compositions are now authorized for that level

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New redaction of conditions 1 & 2 taking into account:

1. The problems found with some cements NF P 15 319 (ES) (resisting to water with high sulfate content) that are not efficient

2. The new european standard on Sulfate Resisting cement (SR0, SR1, SR3 and SR5)

with a specific methodology to qualify SR3 and SR5 (see new annex 5)

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Modification of the annex dealing with the estimation of the temperature reached in the structure (see new annex 4)
Level of prevention As (unchanged)

✓ Tmax < 85 °C

✓ If not: 85 °C < Tmax < 90 °C

and for controled thermal treatment:

duration (Temperature > 85 °C) < 4 hours
Level of prevention Bₚ

✓  \( \text{Tmax} < 75 \degree \text{C} \)

✓  \( 75 \degree \text{C} < \text{Tmax} < 85 \degree \text{C} \) *

* In this case, one of the 6 following conditions has to be respected:

✓  either (condition 1 – for a controlled thermal treatment):

  duration (Temperature > 75 \( \degree \text{C} \)) < 4 hours

  and

  active Na₂O equivalent of concrete < 3 kg/m³
Level of prevention Bs (New)

✓ or (condition 2) use of a cement conforming to NF P 15-319 (ES) or NF EN 197-1 (SR) except SR3 and SR5, for concrete having a duration (Temperature > 75 °C) > 10 hours.

✓ These cements SR3 and SR5 are allowed for concrete having a duration (Temperature > 75 °C) < 10 hours and active Na₂O equivalent of concrete < 3 kg/m³
Level of prevention Bs (New)

or (condition 3): use of cements CEM I SR3 or SR5 conforming to the certification « NF Liants Hydrauliques » and qualified according a specific methodology described in annex 5, for concrete having a duration (Temperature > 75 °C) > 10 hours.

Specific methodology: (test of performance on a specified composition of concrete enriched in alcalis, with specified thermal cycles adapted to the level of prevention)
Level of prevention Bs (unchanged)

or (condition 4): use of cements non conforming to the standard NF P15-319 (ES) of the type:

- CEM II/B-V (with siliceous fly ash)
- CEM II/B-S (with slag)
- CEM II/B-Q (with Calcined natural pozzolans)
- CEM II/B-(S-V) (with slag and siliceous fly ash)
- CEM III/A
- CEM V

with $SO_3$ of cement < 3%

and $C_3A$ of clinker < 8%
Level of prevention Bs (new)

or (condition 5) use, in combination of a CEM I or a CEM II/A, of:

• fly ash: content > 20 %
• Slag: content > 35 %
• silica fume: content > 10 %
• metakaolin: content > 20 %

and for the binder:

C₃A < 8 % (of the clinker)

and SO₃ < 3% (of the binder)
Level of prevention Bs (unchanged)

✓ or (condition 6) checking of the durability of the concrete with respect to DEF, by mean of the performance test and by satisfying to the criteria (Test method LCPC n°66, 2007)
Level of prevention Cs (New)

✓ Tmax < 70 °C

✓ If not: 70 °C < Tmax < 80 °C *

* In this case one of the 6 previous conditions has to be respected (with adaptation of the temperature thresholds for conditions 1, 2 and 3).
Level of prevention Ds (New)

2 precautions recommended, the first one being a priority

Precaution 1: $T_{\text{max}} < 65 \degree C$

If not, Precaution 2: $65 \degree C < T_{\text{max}} < 75 \degree C$

and respect of the previous condition 2 or 3 or 4 or 5 or 6 (with adaptation of the temperature thresholds for conditions 2 and 3).
Modification of the interpretation criteria for the performance test (LPC n 66)

Suppression of the criteria on the monthly variations (not enough accuracy)

Criterion 1: (unchanged)
the average longitudinal expansion of three specimen is lower than 0.04 % and no individual value exceeds 0.06 % at the 12 months limit;

Criterion 2: (modified)
if the average longitudinal expansion of the three specimen is greater than 0.04 % at 12 months, it is necessary to extend the test duration until the 15th month; in this case:
- the average longitudinal expansion of the three specimen must be lower than 0.06 % at 15 months,
- the cumulative variation of expansion between the 12th and 15th months must be lower than 0.01 %
- and no individual value may exceeds 0.07 % at the end of the 15th month.
Modification of the annex dealing with the estimation of the temperature reached in the structure

<table>
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<tr>
<th>Stage n° 1</th>
<th>Estimation of the heat release at long term by the cement used for construction</th>
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<td>Stage n° 2</td>
<td>Consideration of mineral additions: Determination of the “equivalent heat binder” LEch</td>
</tr>
<tr>
<td>Stage n° 3</td>
<td>Taking into account the impact of the ( W_{\text{eff}}/\text{equivalent binder ratio} ) on the temperature rise</td>
</tr>
<tr>
<td>Stage n° 4</td>
<td>Estimation of the temperature rise without thermal losses</td>
</tr>
<tr>
<td>Stage n° 5</td>
<td>Taking into account the thermal losses</td>
</tr>
<tr>
<td>Stage n° 6</td>
<td>Estimation of the maximal possible initial temperature at delivery</td>
</tr>
</tbody>
</table>
Simplified method

✓ **Necessary data:**

  ✓ $T_{\text{max}}$ according to the level of prevention
  
  ✓ cement content of the concrete: $C$
  
  ✓ content of mineral additions: $A$
  
  ✓ concrete density: $M_v$
  
  ✓ content of effective water in concrete: $W_{\text{eff}}$
  
  ✓ compression strength at 2 days of the cement: $R_{c2}$
  
  ✓ compression strength at 28 days of the cement: $R_{c28}$
  
  ✓ hydration heat of the cement at 120 hours: $Q_{120}$ (if not $Q_{41}$)
  
  ✓ thickness of the element: $E_P$
Stage 1: Estimation of the heat release at infinity for the chosen cement: Replacement of Q41 by Q120 (on request)

For CEM I and CEM II cements: \( Q_m = 1.05 \times Q_{120} \)
For CEM III et CEM V cements: \( Q_m = 1.15 \times Q_{120} \)

If Q120 is not available, then \( Q_m = \max(Q41, Q41 \times Qm/Q41 \text{ ratio}) \)

Relation:
\[
\frac{Q_m}{Q41} = 1.71 - 1.16 \frac{Rc2}{Rc28}
\]
Stage 2: Taking into account the mineral additions

Notion of « equivalent heat binder »: \( \text{LEch} = C + \sum K_i' A_i \)

- \( A_i \): content of addition i
- \( K_i' \): weighing coefficient of addition i

New addition: for metakaolin, \( K_i' = 1 \)

Coefficient for addition i as a function of the thickness of the structural element
Stage 3: Taking into account the impact of the ratio Weff/Eq. binder

The lowest is this ratio, the less hydration is complete, and the less heat is released ➔ corrective factor $\alpha$

A new curve has been adopted (with a new formula):

$$\alpha = 1.29 \left(1 - e^{-3.3 \frac{E_{eff}}{Liant \text{eq.}}} \right)$$
Stage 4: Estimation of the increase of temperature in the absence of thermal losses

✓ A new formula is given for $\Delta T_{\text{adia}}$ in adiabatic conditions (full insulation):

$$\Delta T_{\text{adia}} = \alpha \left( Q_m \times L_{\text{ech}} \right) / \left( C_{\text{th}} \times M_v \right)$$

with

$Q_m$ : maximum heat released on the long term by the cement

$L_{\text{ech}}$ : equivalent heat binder

$C_{\text{th}}$ : thermal capacity of concrete = 1 KJ/(kg. °C)

$M_v$ : density of concrete
Stage 5: Taking into account the thermal losses

Reduction coefficient $R$

No change

$\Delta T = R \times \Delta T_{adia}$

Taking into account the thermal losses
Stage 6: Estimation of the maximal possible initial temperature at delivery

$\Delta T_{\text{initial max}} = T_{\text{max}} - \Delta T$

with

$T_{\text{max}}$: maximum temperature for the given level of prevention

$\Delta T$: Elevation of temperature obtained at stage 5

If the forecast temperature of concrete before pouring is greater than $\Delta T_{\text{initial max}}$, a more precised evaluation of temperature has to be done…
Upper station of the Hakone Komagatake cableway, 20th April, 2017
Thank you for your attention, Arigato, Merci.