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The new version of the French recommendations to prevent disorders due to Delayed Ettringite Formation

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Abstract

The internal sulphate reaction due to Delayed Formation of Ettringite (DEF) is an expansive reaction of concrete that can severely damage structures made with this material. DEF is defined as the formation of ettringite in a concrete after hardening, without any external sulfate supply, but with a water supply. This phenomenon occurs in concretes exposed to frequent moisture or in contact with water, subjected to a relatively high heat treatment (> 65 ° C) or having reached equivalent temperatures for other reasons (concrete in massive elements cast in place, etc.).

In the absence of effective and durable treatment methods to repair or rehabilitate the structures affected by DEF, the LCPC (now IFSTTAR) published in 2007 the first version of the French recommendations for the prevention of disorders due to DEF; an English version was published in 2009. After ten years of application of these recommendations, it was necessary to revise this guide, and a new version was released in 2017, with its English translation in 2018.

The article presents the main evolutions of these recommendations and particularly the modifications made to the precautions by taking into account some recent results of research. They concern the consideration of new additions into concrete, the improvement of the method for calculating the maximum temperature reached inside the concrete at construction, the modification of the interpretation criteria of the performance test for DEF, and some other provisions.

Keywords: *concrete; delayed ettringite formation; prevention; recommendations; revision*

1. INTRODUCTION

1.1 Brief description of the reaction

The expansive sulphate internal reaction due to Delayed Ettringite Formation (DEF) can damage concrete structures severely. The primary ettringite (a hydrous calcium trisulphoaluminate) is a normal reaction product formed from the reaction of C3A and C4AF with gypsum during the plastic stage of the hydration of Portland cement. However, when peak temperatures in concrete are over about 65°C, the sulphates may be incorporated in other cement phases. After concrete hardening, the very slow formation of higher volume secondary ettringite may occur as water is taken into the crystal structure which can lead to potentially disruptive expansion. DEF is defined as the formation of ettringite in a concrete after setting, and without any external sulphate supply, but with a water supply. DEF appears in concretes exposed to frequent humidity or contact to water, and subjected to a relatively high thermal treatment (> 65°C) or having reached equivalent temperatures for other reasons (massive cast-in-place concrete, concrete casting during summer, etc). DEF affects the interior concrete without any ingress of external sulphates, and leads to a concrete swelling and the cracking of the structure.

1.2 Occurrence of damaged structures

The first reported cases of DEF occurred in some precast concrete elements subjected to a heat treatment unsuited to the composition and the environment of the concrete. International examples of DEF include railway sleepers [1] to [8], and massive cast-in-place concrete components [9] to [12].

DEF was first observed in France, in 1997 [13], on bridges whose concrete had been cast on site. The bridge parts damaged by DEF were primarily massive structural elements (piers, crossbeams on piers or abutments, etc.) in contact with water or subjected to high moisture. Then, some bridges decks composed of precast concrete beams were discovered as affected by DEF; longitudinal and shear cracks developed in these beams and the main cause could be attributed to the use of a high temperature cycle during the heating phase in the factory. In France, now, about one hundred and fifty bridges and a few dams are damaged by DEF to a more or less extent. Some examples are presented in [14], and lessons learned from these cases were considered to elaborate a prevention strategy [15].

The first French recommendations for the prevention of damage due to DEF were published by LCPC (Laboratoire Central des Ponts et Chaussées) in 2007 [16] and its English version was published in 2009. Then a revised version of these recommendations was released by IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux) in 2017 [17], with its English version in 2018.

Since 2007, no new case of DEF has been found in structures built after 2007 and designed according to the LCPC Recommendations. Despite this fact proving that the global methodology of prevention released in 2007 seems to be effective, the return of experience arising from the field, the new results of the research conducted in various laboratories since 2007, the release of the new European standard on sulphate resisting (SR) cements, the placing on the market of new additions for concrete and the need to improve the calculation method for estimating the temperature reached in a structure resulted in the necessity to adapt and to revise these recommendations. After the recall of the prevention methodology and the presentation of some research results, the main modifications will be presented.

2. REMIND OF THE FIRST VERSION OF THE RECOMMENDATIONS

2.1 Principles

The principles of the prevention of disorders due to DEF presented in the technical recommendations released by LCPC in 2007 [16] have not be modified in the new version. The prevention methodology adopted in these recommendations is strongly inspired from the methodology adopted by LCPC for the prevention of alkali-aggregate reaction in 1994. It consists in identifying the parts of structures likely to develop disorders due to DEF. They are primarily the parts of structures defined as being "critical parts" (i.e. concrete parts for which the generated heat is only partially dissipated towards outside and leads to a high rise of the concrete temperature) and precast products having been subjected to externally applied heating. Then a cross analysis is carried out between the following two paramount parameters:

- the category in which the structure (or a part of it) is classified according to the level of risk of occurrence of disorders that can be accepted by society
- the environmental conditions to which the structure is exposed during its service life.

This analysis allows to define a level of prevention which determines the precautions that have to be applied. These precautions are mainly based on the limitation of the maximum temperature reached within the heart of the structure parts during hardening of the concrete, and on the choice of an adequate composition of the concrete.

2.2 Choice of the structure category

The structures (or parts of them) are classified in 3 categories that are representative of the level of risk with respect to DEF that are acceptable for a given structure (or a part of it). The choice of the structure category is a function of the nature of the structure, its purpose, the consequences of the disorders in relation with the desired safety level, and its future maintenance:

- Category I refers to the structures (or parts of structure) for which the consequences of the occurrence of disorders are low or acceptable.
- Category II gathers the structures (or parts of them) for which the consequences of the occurrence of disorders present low tolerance.
- Category III corresponds to structures (or parts of them) for which the consequences of the occurrence of disorders are unacceptable or quasi unacceptable.

Table 2.1 gives some examples of the classification of structures in the three categories.

Table 2.1: Examples of structures or parts of structures classified by category

Category	Examples of structures or parts of structures
Category I (low or acceptable consequences)	Concrete structures with a compressive strength class < C 16/20 Non structural elements inside buildings Elements that are easy to replace, temporary structures Most of non structural precast products
Category II (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 (unacceptable or quasi unacceptable consequences)	Nuclear power plants and atmospheric cooling towers Dams, Tunnels, Exceptional bridges and viaducts Monuments or prestigious buildings Railway sleepers

2.3 Choice of the exposure class

The new standard NF EN 206 which defines many classes of exposure relating to the various possible concrete attacks, does not define a class of exposure well suited to the internal sulphate reaction associated with delayed ettringite formation. This is why the recommendations introduce three complementary classes in relation to this standard: XH1, XH2 and XH3. Those classes take into account the fact that water or a high ambient humidity are factors necessary for the development of DEF. The contribution of alkalis and sulphates by the surrounding environment causes also an increase of disorders, but it is considered that they form part of a process of surface degradation and that they are concerned by preventive measures that are treated in other documents. Three exposure classes XH1, XH2 and XH3 are defined according to indications of table 2.2 that also presents, on a purely informative basis, examples of structural parts classified in the suitable ambient conditions.

Table 2.2: Environmental classes of a structural part with respect to DEF

Exposure class	Description of the environment	Informative examples illustrating the choice of the exposure classes
XH1	Dry or moderate humidity	Parts of concrete structure located inside buildings where the humidity content of the ambient air is low or average Parts of concrete structure located outside and sheltered from the rain
XH2	Alternation of humidity and drying High humidity	Parts of concrete structure located inside buildings where the humidity content of the ambient air is high Parts of concrete structure not protected by a coating and subjected to the bad weather, without water stagnation on the surface Parts of concrete structure not protected by a coating and subjected to frequent condensations
XH3	In prolonged contact with water: permanent immersion, water stagnation on the surface, tidal zone	Parts of concrete structure submerged permanently in water Elements of marine structures A great number of foundations Parts of structure regularly exposed to sprayed water

2.4 Choice of the prevention level

The level of prevention is determined by crossing the structure category and the exposure class XH to which the considered part of the structure is subjected. The determination of the level of prevention can be done by considering the whole structure, but it is recommended to examine each part of the structure to determine the adapted level of prevention. Unlike the AAR recommendations where three levels were adopted, four levels of prevention were considered for DEF, indicated by the letters As, Bs, Cs and Ds. The choice of the prevention level is clearly the responsibility of the structure owner who can be helped for that purpose by table 2.3.

Table 2.3: Choice of the level of prevention

Category of structure	Exposure class of the structural part		
	XH1	XH2	XH3
I	As	As	As
II	As	Bs	Cs
III	As	Cs	Ds

As an example of application, in the case of a bridge classified in category II, the piles and the foundation slabs may fall under the level of prevention Cs because there is a strong risk of permanent contact with water, whereas the piers and the deck protected by a waterproofing membrane may come with the level of prevention Bs. For the crossbeams on piers or on abutments, the prevention level will be chosen in respect with the provisions taken to ensure the drainage on these structural parts: the level of prevention will be Bs or Cs according to the risks of water stagnation.

2.5 Precautions associated to a prevention level

The type of precaution to be applied is directly related to each of the four levels of prevention As, Bs, Cs and Ds. The principle of prevention is resting primarily on the limitation of the heating of the concrete characterized by the maximum temperature Tmax likely to be reached within the structure and, if necessary, by the duration of the period where a high temperature is maintained.

In the case where the maximum temperature recommended in agreement with the level of prevention is exceeded, several complementary solutions are sometimes proposed.

The precautions corresponding to the four levels of prevention are the following ones:

• Level As: Tmax < 85 °C

however in the case of a heat treatment applied on a precast element, it is authorized to go beyond the temperature Tmax = 85 °C until 90 °C, provided that the duration of the time period during which the temperature exceeds 85°C is limited to 4 hours.

• Level Bs: Tmax < 75 °C

however if the maximum temperature reached in the concrete cannot remain lower than 75°C, then it must remain lower than 85 °C and at least one of the six conditions given in table 4 of the recommendations [16] must be respected.

• Level Cs: Tmax < 70 °C

however if the maximum temperature reached in the concrete cannot remain lower than 70°C, then it must remain lower than 80 °C and at least one of the six conditions given in table 4 of the recommendations [16] must be respected.

• Level Ds: Tmax < 65 °C

For this highest level of prevention, the risk of developing DEF must be taken into account by one of the two following precautions, the first precaution being recommended as a priority:

-- Precaution 1: Tmax < 65 °C

-- Precaution 2: If Tmax cannot remain lower than 65 °C, then it must remain below 75°C with the respect of the 2 following conditions:

- Respect of condition 2 in table 4 of the recommendations [16]
- Validation of the concrete composition by an independent laboratory expert in DEF

The six conditions numbered from 1 to 6 are not recalled here because they were substantially modified in the new version; they can be found in reference [18].

2.6 Performance test for DEF

The condition 5 mentioned above is referring to a performance test on concrete cores which was developed by LCPC [19-21] and aims at characterizing the swelling risk of a concrete with respect to DEF. The concrete is defined simultaneously by its composition and by the heating to which it is exposed during its curing. The test comprises four distinct stages: the manufacture of the concrete, the heat treatment simulating the heating of the concrete, the cycles of drying and humidification, and the final immersion in water at a temperature of 20 °C and the follow-up of the longitudinal deformations.

The minimal duration of this test is 12 months of immersion, and it can be extended up to 15 months when a significant expansion is measured. The set «concrete composition and heating» is considered suitable to use if one of the two following criteria (criterion 1 or criterion 2) focusing on the expansion threshold and the slope of the expansion curve is respected:

Criterion 1:

- the average longitudinal expansion of three specimen is lower than 0,04 % and no individual value exceeds 0,06 % at the 12 months limit;
- and any monthly variation of the average longitudinal expansion of the three specimen measured from the 3rd month is lower than 0,004 %.

Criterion 2:

- the individual longitudinal expansion of three specimen lies between 0,04 % and 0,07 % at the 12 months limit. In this case, it is necessary to extend the test until the 15th month;
- and any monthly variation of the average longitudinal expansion of the three specimen measured from the 12th month is lower than 0,004 %, and the variation between the 12th month and the 15th month is lower than 0,006 %.

2.7 Prevention measures during construction and service

The principal preventive measures for construction aim at avoiding extended contacts with water during the service period of the structure, limiting the maximum temperature reached within the concrete in the critical parts, and controlling the heating treatments of the precast units. To avoid the contacts between the critical parts of a structure and water, the structure must be designed in order to avoid the existence of zones of accumulation and stagnation of water, as well as preferential routes of water runoff.

The limitation of the temperature rise may be obtained by various means such as the choice of the least possible exothermic cement, the substitution of a part of cement by mineral additions, the cooling of the concrete elements, the modification of the design of massive parts to transform them into hollow elements, the avoidance of concrete setting of critical structural elements during strong heats, the choice of a night period to minimize the temperature of the fresh concrete... Reference [18] gives more details on these prevention measures.

3. RESEARCH RESULTS

In order to update the recommendations published in 2007, it was decided to gather the feedback from their applications in the field, and to update the proposed mitigation rules by considering the last published relevant research results on this topic. It was also necessary to take into account the last version of the French concrete standard NF EN 206/CN which allows a wider use of CEM II/A-L&LL cements for concrete mix designs. It has to be noted that, blended Portland cement incorporating up to 20 % Calcium Carbonates (CEM II/A-L or LL as per European EN 197-1 terminology) are becoming more and more popular in concrete industry worldwide in particular to mitigate carbon footprint of Portland cements (CEM I). Furthermore, the influence of Calcium Carbonates on DEF reaction development has been questioned [22-24].

In order to assess the efficiency of several proposed concrete mixes designed with different mineral additions for DEF risk mitigation, we conducted two studies: the first with LNEC (Laboratorio Nacional de Engenharia Civil – Portugal) and the second with FNTP (French Federation of Public Works Contractors).

3.1 Results of the LNEC research

LNEC study [22, 23, 25] presents the findings of 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 SO_3 = 2,7%, Cement Na_2Oeq = 1,2%). The mineral additions tested with various contents 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%) and limestone filler (10, 15, 20 and 30%). The heat-curing cycle used was based on the temperature reached by concrete cores during setting of a massive cast-in-place concrete. The concrete reached a maximum temperature of 80°C after 15 hours and was maintained at temperatures above 70°C during 3 days. The results show that the mineral additions have a strong effect for the inhibition of the expansion due to DEF, with the exception of limestone filler for which there is an increase in expansion. 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 and 10% for silica fume [25]. See also the paper presented in this conference by Silva & al. [28].

3.2 Results of FNTP and IFSTTAR research

The FNTP, with the help of IFSTTAR, has launched in 2014 an extensive testing program [26] considering around 20 different concrete mixes comparatively tested through the French standardized concrete long term performance test protocol with thermal cycles corresponding to massive cast-in-situ elements. The choice of relevant manufactured cements (CEM I and CEM II/A-LL) produced with the same clinker at the cement plant was made by considering conservative parameters as far as DEF risk is concerned (clinker C3A = 10%, Cement SO_3 = 3,5%, Cement Na_2Oeq = 0,6%). The following mineral additions, with their respective cement replacement percentage, were selected for the experimental study: ground granulated blast-furnace slag (35, 40, and 60% in mass), fly ash (20 and 30%), metakaolin (20%), silica fume (10%). For the concrete mixes designed with the selected CEM II/A-LL containing 15% of additions, additional limestone filler (30 kg/m^3) was added in order to reach artificially an overall content of about 22 % of Calcium Carbonates within the cementitious material which corresponds to the maximal allowed concentration of CEM II/A, including +/- 2 % variation specified in EN 197-1. Siliceous aggregates from the “Palvadeau” quarry (Non-Réactive to Alkali-Silica Reaction) were used. The following parameters have been considered and kept constant for the whole experimental study:

- total binder = 400 kg/m^3
- siliceous aggregates = 1800 kg/m^3
- free water / total binder = 0.45
- slump = 180 +/- 30 mm adjusted with different contents of polycarboxylate high-water range reduction admixture.

Two concrete thermal cycles were taken into account for this experimental study:

- Cycle n°1: Peak threshold 75°C during 3 days
- Cycle n°2; Peak threshold 85°C during 3 days.

The thermal cycles kinetic has been inspired from field temperature records corresponding to massive cast-in-situ elements.

The influence of mineral additions when used with cement CEM II/A-LL (22% of $CaCO_3$) is shown in figure 3.1. The reference concrete (CEM II/A without mineral additions) exhibits as expected a very high expansion. The maximal swelling is equal to about 1.3%. Mineral additions are showing good efficiency to mitigate DEF expansion. For each of the following considered mineral addition: 40% and 60% of ground granulated blast-furnace slag (GGBF), 20% and 30 % of fly ash (FA), the recorded expansions of specimen remain below 0.05% after 700 days. . Also, it can be concluded that calcium carbonates included within cement do not alter the inhibiting impact of either Ground Granulated Blast-Furnace Slag or Fly Ash as far as DEF is concerned.

The influence of mineral additions when used with cement CEM I and thermal cycle 1 is shown in figure 3.2. With thermal cycle 1 at 75°C, the considered mineral additions and their associated considered substitution rate (35% for ground granulated blast-furnace slag, 20% for fly ash, 20% for Metakaolin (MK) and 10% for silica fume (SF)) mitigate DEF reaction. The expansion kinetic and amplitude of sample with mineral additions are identical whatever the considered mineral additions type with a plateau around 0.05%.

In conclusion, this large experimental study allows confirming inhibiting properties of mineral additions when used in sufficient proportion for partial substitution of Portland cement. The same conclusion remains when mineral additions are used in partial substitution of cement with Calcium Carbonates (CEM II/A-LL).

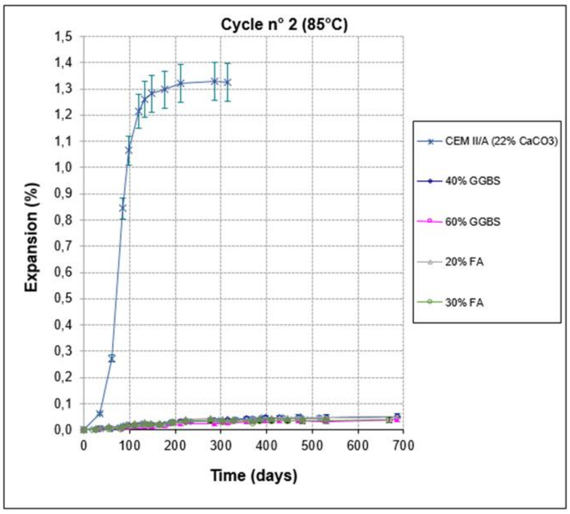

Figure 3.1: Influence of mineral additions on DEF in the presence of cement CEM II/A LL with 22% CaCO3 (FA = fly ash, GGBS =slag).

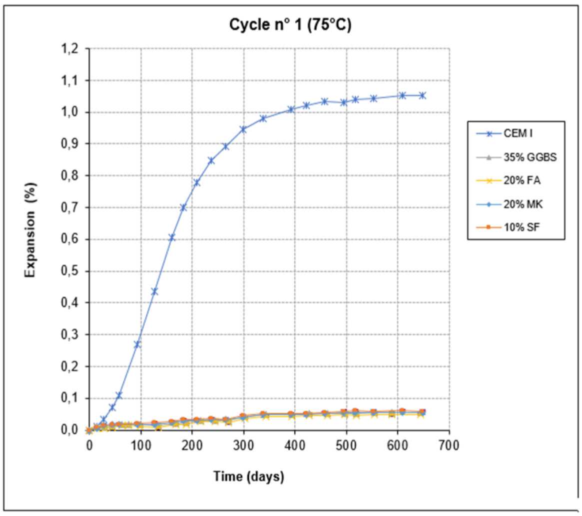

Figure 3.2 : Influence of mineral additions on DEF in the presence of cement CEM I (FA = fly ash, GGBS =slag, MK = metakaolin, SF = silica fume).

4. MODIFICATIONS BROUGHT TO THE RECOMMENDATIONS

Based on a ten year return of experience in the application of the 2007 recommendations, it was decided to keep the definitions and characteristics of the categories, exposure classes and levels of prevention. It was also decided to keep the values of the maximal temperature (85°C, 75°C, 70°C and 65°C) corresponding respectively to the levels of prevention (As, Bs, Cs and Ds), and to delete the condition 6 on references of use for precast products because this solution was quite impossible to apply.

4.1 Modifications of the precautions

The results of the LNEC and FNTP studies indicate that the use of standardized mineral additions (Ground Granulated Blast-Furnace Slag, Fly Ash and Silica Fume), even when used with Calcium Carbonates based blended cement, can significantly mitigate the DEF risk irrespectively of their beneficial effect on concrete temperature development in massive elements and heat-cured precast elements.

Beyond these studies, the modifications introduced for the precautions concern the levels Bs, Cs and Ds. For the levels Bs and Cs, the new condition 5 allows today to use silica fume with a substitution percentage greater than 10% and ground granulated blast-furnace slag with a substitution percentage that is increased from 20 % to 35%. The new condition 5 allows a use of CEM II/A-L&LL with mineral additions for concrete mix designs.

For the level Ds, the validation of concrete composition by an independent laboratory expert in DEF has been deleted. The conditions 4 and 5 are now authorized for this prevention level.

Table 4.1 presents the new conditions usable when the temperature threshold is exceeded.

Table 4.1: The six conditions usable when the temperature threshold is exceeded

Condition 1	Condition 2	Condition 3
- Duration < 4 hours while maintaining the concrete temperature above 75°C for Bs and above 70°C for Cs AND - Equivalent active alkalis of the concrete < 3 kg/m^3	Use of a cement conforming to: - standard NF P 15-319 (ES) OR - to the classes SR0 and SR1 as specified in NF EN 197 for concretes which are expected to reach a temperature in excess of 75 °C for more than 10 hours OR - to the classes SR3 and SR5 for concretes which are expected to reach a temperature in excess of 75 °C for less than 10 hours, with the condition that the equivalent active alkalis of the concrete < 3 kg/m^3	Use of a CEM I SR3 or SR5 cement which complies with the NF Liants hydrauliques (French Standard Hydraulic Binder) marking AND which has been characterized using the methodology set out in Appendix 5 of the Recommendations, in the case when the temperature remains above 75 °C for more than 10 hours.
Condition 4	**Condition 5**	**Condition 6**
Use of cements which do not comply with the standard NF P 15-319 (ES) of the types : - CEM II/B-V, CEM II/B-Q, CEM II/B-M (S-V) with the condition they contain more than 20 % of fly ash, - CEM III/A or CEM V, all of which should have an SO3 content which does not exceed 3 %, and the clinker introduced during cement manufacture must not contain more than 8 % of C3A	Use, in combination with CEM I or CEM II/A, of fly ash, or ground blast-furnace slag, or silica fume, or metakaolin. The proportions of these additions in the binder must be less than : - 20 % for fly ash - 35 % for blast furnace slag - 10 % for silica fume (note 1) - 20 % for metakaolin. The binder used must meet the following requirements: - C3A (as a proportion of the clinker) < 8 % - SO3 (as a proportion of the binder) < 3 %.	Verification of concrete durability with respect to DEF by relying upon performance testing and by satisfying a number of decision-making criteria.

Note 1: In the case of silica fume this limit may be reduced to 5 % as long as the binder contains at least 15 % of fly ash
Note 2: According to EN 197-1:
CEM I is a cement containing clinker
CEM II/A-L (or LL) is a cement containing clinker and 6-20% of limestone
CEM II/B-V is a cement containing clinker and 21-35% of fly ash
CEM II/B-S is a cement containing clinker and 21-35% of ground granulated blast-furnace slag (GGBS)
CEM II/B-Q is a cement containing clinker and 21-35% of natural pozzolan
CEM II/B-M (S-V) is a cement containing clinker and 21-35% of fly ash and GGBS
CEM III/A is a cement containing clinker and 36-65% of ground granulated blast-furnace slag
CEM V is a cement containing clinker and 18-30% of natural pozzolan or fly ash and 18-30% of GGBS
Note 3: NF P 15-319 (ES) is a French standard for cement resisting to water or soils having a high content of sulphates

4.2 Modifications of the interpretation criteria of the performance test

Because it was difficult to measure with enough accuracy the monthly variation of the average longitudinal expansion of specimen in order to respect the stringent previous rules, it was decided to delete the conditions relative to this monthly rate and the criteria are modified as follows:

Criterion 1:

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:

If the mean longitudinal expansion of the 3 specimens exceeds 0.04 % upon expiration of the 12-month period, the test must be extended through the 15th month. In this case, the mean longitudinal expansion of the 3 specimens must be less than 0.06 % at 15 months, and the cumulative variation between the 12th and 15th months must remain below 0.01 %, and moreover no individual value may exceed 0.07 % at 15 months.

4.3 Modifications of the estimation of the temperature reached in a structure

It was decided to improve the calculation method to estimate the temperature reached in a structure and described in the appendix 4 of the previous recommendations. This appendix is intended to propose a simplified methodology for assessing whether some elements need to be considered as critical with respect to the risks of delayed ettringite formation (in correlation with the risk of excessive temperature at the core of cast elements). The appendix thus makes it possible to estimate the maximum temperature rise at the core of an element for which only the thickness (at its smallest dimension) and a small amount of basic data on concrete composition are known. On the basis of the maximum temperature Tmax which must not be exceeded at the core of the element, the maximum possible initial temperature Tini_max of the fresh concrete during concreting is deduced. The 6 steps of the methodology are presented in the following flowchart (Figure 4.1).

STEP 1
Estimation of the heat release at infinite time for the selected cement:
determination of Qm (Q41, Rc2/Rc28)

↓

STEP 2
Incorporation of mineral additions:
Determination of the heat equivalent binder LEch (type and quantity of mineral additions, EP, C)

↓

STEP 3
Incorporation of the impact of Eeff/LEch ratio on temperature rise:
Determination of a corrective term α (Eeff/LEch)

↓

STEP 4
Estimation of the temperature rise in the absence of thermal losses:
determination of ΔTadia (Qm, LEch, Cth, Mv, α)

↓

STEP 5
Incorporation of thermal losses:
Determination of a reduction coefficient R to assign to ΔTadia in order to estimate temperature rise of the element ΔT

↓

STEP 6
Estimation of the maximum possible initial temp. of the fresh concrete during concreting:
Determination of Tini_max (ΔT,Tmax)

Figure 4.1: Flowchart presenting the sequence of calculation steps

At the first step of this method, the heat Qm (in J/g) released on a long term by a cement was calculated in the previous recommendations by multiplying the heat released by the cement at 41 hours by the ratio Qm/Q41 given as a function of the compressive strength ratio Rc28/Rc2. The new recommendations propose to improve the estimation of Qm by considering the heat released by the cement at 120 hours: Q120. If this value improves the prediction, it underestimates the Qm values of CEM III and CEM V cements; therefore the following relations are to be applied:

- for CEM I and CEM II cements: Qm = 1.05 Q120
- for CEM III and CEM V cements: Qm = 1,15 Q120

Q120 is not a standardized value and it should be given by the cement producer on request by the client. But if this value is not available, then the calculation of Qm is based on Q41 and the following relations are applied:

$$Qm = \max(Q41, Q41 \times \_Qm/Q41 \text{ ratio}) \quad (1)$$

where the value of the_Qm/Q41 ratio is given by the following equation:

$$Qm/Q41 = 1{,}71 - 1{,}16\ Rc2/Rc28. \quad (2)$$

where Rc2 and Rc28 are respectively the 2-day and 28-day compressive strength of the cement (in MPa), according to Standard NF EN 196-1.

In the second step of the method, the additions which are participating to the heat release are considered via an equivalent heat binder LEch (in kg/m³) given by the following formula:

$$LEch = C + \sum K_i'\ A_i \quad (3)$$

where C is the cement content, and Ai and Ki' are respectively the content and the weighing coefficient of the i addition. In this step, the new metakaolin addition is added with a value K' = 1 as for the silica fume (see figure 4.2).

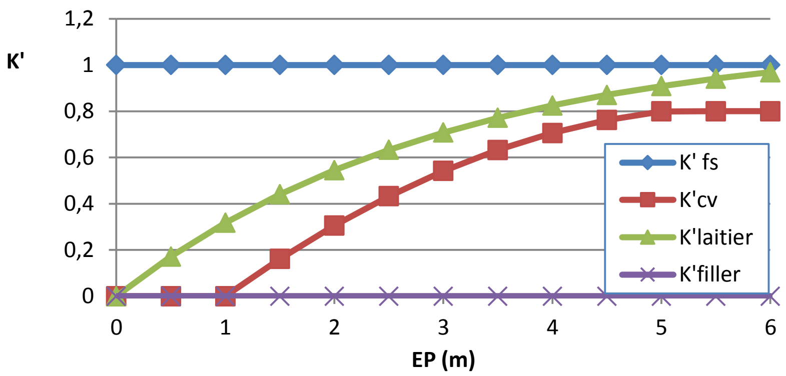

Figure 4.2: K' coefficient of additions for the calculation of the equivalent heat binder Lech as a function of the width of the structural element EP (fs = silica fume, cv = fly ash, laitier =slag).

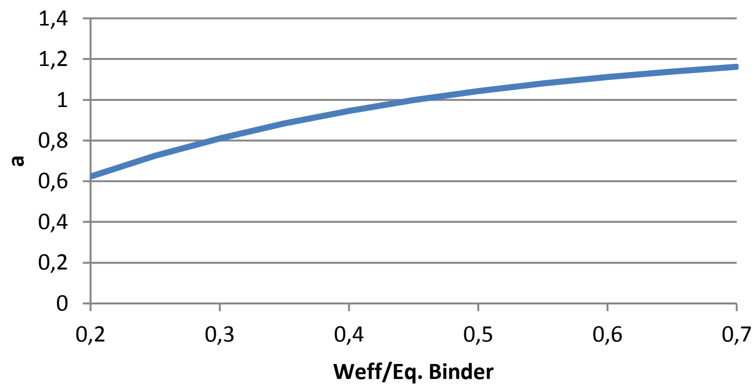

Figure 4.3: Correction of the heat rise linked to the Weff/Equivalent binder ratio.

The third step introduces a coefficient α in order to take into account the fact that the temperature rise resulting from the heat released by the binder also depends on the Weff/Equivalent binder ratio (effective water divided by equivalent binder) which determines the maximum long-term rate of hydration. Equation 4 gives the formula to calculate α and Figure 4.3 shows how this corrective term varies with the ratio Weff/Equivalent Binder. The formula is calibrated to give no correction (α = 1) for a Weff over equivalent Binder ratio equal to 0.45.

$$\alpha = 1.29\,(1 - e^{-3.3\,(\text{Weff/ Eq. Binder})}) \quad (4)$$

At the fourth step, it is possible to evaluate the temperature rise ΔT_{adia} (°C) under adiabatic conditions (i.e. perfect insulation) based on the following formula (equation 5):

$$\Delta T_{adia} = \alpha\,(Qm \times LEch) / (Cth \times Mv) \quad (5)$$

where Cth is the thermal capacity of the concrete taken equal to 1 kJ/(kg .°C).

Then, the fifth step (incorporation of thermal losses) is not modified and the sixth step gives the initial maximum temperature of the concrete Tini_max that is calculated by the formula:

$$Tini\_max = Tmax - \Delta T \quad (6)$$

where Tmax is the maximum allowable temperature for the concrete in the structure and ΔT the temperature rise computed at the end of step 5.

5. CONCLUSION

The internal sulphate reaction due to delayed ettringite formation has been discovered more than thirty years ago in some precast elements subjected to heating, and it is only about fifteen years ago that this reaction was found in cast in place bridge elements whose concrete has reached high temperature. This rather recent discovery explains the small number of studies and research devoted to this problem.

As regards prevention, it is advisable to note the important work undertaken in France by the LCPC with the assistance of the cement industry and the civil engineering contractors to develop recommendations intended to avoid the occurrence of new disorders, despite the relatively low level of knowledge on the subject. Efforts were also made to develop an accelerated expansion test on concrete subjected to DEF, with the objective of going towards a performance approach. If the return of experience with the application of this new version of the recommendations appears to be positive in a few years, it will be proceed towards a standardization.

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