THE NEW FRENCH RECOMMENDATIONS TO PREVENT DISORDERS DUE TO DELAYED ETTRINGITE FORMATION

Bruno Godart[*], Loïc Divet

Laboratoire Central des Ponts et Chaussées (LCPC), PARIS, France

Abstract

These recommendations deal with civil engineering structures and buildings comprising elements of important size that are in contact with water or subjected to a humid environment. They present the different levels of prevention that have to be determined according to the category of the structure (or part of the structure) and to the environmental conditions to which it is exposed. For each of the four levels of prevention selected, associated precautions are applied and associated verifications are carried out. The recommendations also present preventive measures related to the design and erection of the structures, the formulation and the manufacture of the concrete as well as to its pouring. These preventive measures aim at avoiding the prolonged contact of the critical elements with water during the service life of the structure, at limiting the maximum temperature reached within the concrete of the critical elements, and at controlling the heating treatments of the precast elements.

KEYWORDS: DEF, prevention, recommendations, heat limitation, concrete composition

1 INTRODUCTION

The sulphate internal reaction due to delayed ettringite formation (DEF) is a cause of disorders likely to damage concrete structures with severity. The first cases appeared abroad from 1987 [12] in certain precast elements which had been subjected to a heat treatment unsuited to the composition and the environmental of the concrete (like, for example, railway sleepers). This phenomenon was observed in France, since 1997, on bridges whose concrete had been cast on site [14]; they are primarily massive structural elements (piers, crossbeams on piers or abutments, etc.) in contact with water or subjected to high moisture. Differing from the more traditional sulphate reactions where the sulphates attack the concrete from outside and create a progressive degradation from the surface towards the heart of the element, DEF affects the whole concrete without calling upon an external source of sulphates. It leads to a concrete swelling and the cracking of the structure.

2 DAMAGED STRUCTURES IN FRANCE

In France, the discovery of the DEF and its deleterious demonstrations is recent, with the first cases identified during the 1990s. This phenomenon was mainly observed in massive parts of concrete bridges cast in place during the hot season [2 and 14]. According to an inventory made by LCPC (Central Laboratory for Roads and Bridges), the number of cases of damaged structures is for the moment very small (approximately about thirty), but it generally concerns current civil engineering structures. In these structures, the concrete is deteriorated by DEF and is not subjected to any particular alkali-silica reaction. Generally, the disorders are visible on a structure between five and ten years after its construction. Moreover, these disorders never affect the whole structure, but primarily affect the massive parts exposed to humidity or to water. The concrete was subjected to an important heating which could lead to a temperature of about 80 °C, the latter resulting from the geometry of the part, the period of casting (in summer) and a high cement content.

A more detailed expertise was carried out on eight bridges in order to seek the parameters that were simultaneously present and, a priori, necessary for the development of DEF [2]. These parameters were classified in four groups, related to the:

- temperature,
- cement,
- concrete, and
- environment.

These data are collated in table 1.

[*] Correspondence to: bruno.godart@lcpc.fr

3 PREVENTION OF THE DISORDERS

3.1 Principles of prevention

The prevention of the disorders due to DEF is the subject of LCPC technical recommendations [15]. The methodology of prevention followed in these recommendations 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, on the one hand 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, and on the other hand the environmental conditions to which the structure (or a part of it) is exposed during its service life. This analysis makes it possible 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.

3.2 Choice of the level of prevention

Before defining the level of prevention, it is first of all advisable to introduce the concepts of structure category and exposure class.

Structure category

The structures (or parts of them) are classified in 3 categories 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 according to the desired safety level, and of 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. The majority of the precast concrete products are included in this category except for the structural precast elements and the products intended to be used in aggressive environments (acoustical barriers, bridge cornices, some drainage pipes,…).

Category II gathers the structures (or parts of them) for which the consequences of the occurrence of disorders present low tolerance. Load bearing elements of most of the buildings and civil engineering structures (among them the current bridges) are included in this category, as well as the precast structural elements.

Category III corresponds to structures (or parts of them) for which the consequences of the occurrence of disorders are unacceptable or quasi unacceptable. In general, they are structures with an exceptional character whose total absence of disorders can be required for safety or esthetical reasons, or impossibility of repair or replacement.

Table 2 gives some examples of classification of structures in the three categories.

Exposure classes with respect to DEF

The standard NF EN-206-1 which defines many classes of exposure relating to the various possible aggressions of the concrete, does not define a class of exposure adapted to the internal sulphate reaction associated with delayed ettringite formation. This is why the LCPC recommendations [15] 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 which are treated in other documents (for example in standard NF EN 206-1).

These three exposure classes XH1, XH2 and XH3 are defined according to indications of table 3 which also presents, on a purely informative basis, examples of structural parts classified in the suitable ambient conditions.

Levels of prevention

The determination of the level of prevention is done according to the category of the structure 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. The choice of the levels of prevention indicated by the letters As, Bs, Cs and Ds, is the responsibility of the structure owner which can be helped for that by table 4.

As an example of application, in the case of a bridge classified in category II, the piles and the foundation slabs can be relevant to a level of prevention Cs, whereas the piers and the deck can be concerned by a level of prevention Bs. For the crossbeams on piers or on abutments, the choice of the prevention level will be done according to the provisions taken to ensure the drainage on these parts of structure: the level of prevention will be Bs or Cs according to the risks of water stagnation.

3.3 Precaution to be adopted according to the level of prevention

The type of precaution to be applied corresponds to each of the four levels of prevention As, Bs, Cs and Ds. The principle of prevention rests primarily on the limitation of the heating of the concrete characterized by the maximum temperature T_{max} likely to be reached within the structure and, if necessary, by the duration of the period where the high temperature is maintained. In the case where the maximum temperature advised according to the level of prevention is exceeded, several solutions of replacement are sometimes proposed.

The precautions corresponding to the four levels of prevention are as follows:

- As level: T_{max} < 85 °C

However, for heat treatment in a precasting plant, it is allowed to go beyond the temperature T_{max} = 85 °C up to 90 °C, provided that the time the temperature exceeds 85 °C is limited to 4 hours.

- Bs Level: T_{max} < 75 °C

However, if the maximum temperature reached in the concrete exceeds 75 °C, then it must remain lower than 85 °C and at least one of the six conditions given in table 5 must be respected.

- Cs level Cs: T_{max} < 70 °C

However, if the maximum temperature reached in the concrete exceeds 70 °C, then it must remain lower than 80 °C and at least one of the six conditions given in table 5 must be respected.

- Ds Level:

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

-- Precaution 1: T_{max} < 65 °C

-- Precaution 2: If T_{max} cannot remain lower than 65 °C, then it must remain lower than 75 °C by observing the 2 following conditions:
  - Use of a cement conforming to the French standard NF P 15-319 (ES) with, in the case of the CEM I and CEM II/A, the limitation that the content of equivalent active alkalis in the concrete remains below 3 kg/m^3
  - Validation of the concrete composition by an independent laboratory expert in DEF.

3.4 Construction preventive measures

The principal preventive measures to avoid the activation of delayed ettringite formation in building and construction aim at avoiding extended contacts with water during the period of use of the structure, at limiting the maximum temperature reached within the concrete in the critical parts, and at controlling the heating treatments of the precast units.

Avoiding extended contacts with water

To avoid the contacts of the critical parts with water, the structure must be conceived so as to avoid the existence of zones of accumulation and stagnation of water, as well as preferential routes of water runoff. This requires profiles and slope forms allowing a fast drainage of water. It is particularly the case with bridge decks where it is required to set a waterproofing membrane and to install drainage devices for water which are effective and regularly maintained.

The application of a protection coating on concrete is also a solution to avoid the reaction by minimizing the ingress of water in the structure. The most effective protection coatings are those having a great thickness (a few millimetres) and sufficiently tight with respect to water and vapour. It is a solution which can be used to complement a more reliable solution of prevention, but not to ensure in a final way the prevention of DEF, because it requires a regular repair of the coating. In addition it is almost impossible to seal supports founded in water, like piers in river, insofar as one cannot oppose the capillary forces; in this case, it is advisable to adopt provisions aiming at reducing important temperature rises.

Limiting temperature rises

The choice of the least possible exothermic cement, the substitution of a part of cement by mineral additions (slags, fly ash, pozzolans,…) or the reduction of the cement content are solutions which make it possible to reduce the heating of the concrete and thus the temperatures reached within the critical parts. The LCPC recommendations [15] indicate as an example, that the replacement (in the composition of a concrete) of a cement CEM I 52,5 N by a cement CEM III 42,5 N (in an element having a thickness of 1m) results in a reduction of the maximum temperature of approximately 15°C.

This solution must however be in agreement with the other requirements related to construction like the early strength of concrete, workability, durability,… In certain particular cases, like the simultaneous resistance of the concrete to freeze-thaw and DEF, it appears sometimes difficult to accommodate all the requirements; this is why other measures besides those related to concrete composition must also be considered to limit the temperature rise.

Among these measures, some are related to the cooling of the concrete elements: the use of cold or cooled mixing water, the cooling of the aggregates (water spraying on the gravels), the protection of aggregate stocks against the sun, or the substitution of a part of the mixing water by ice. If the first two methods are relatively simple to apply, the use of ice is more delicate: it requires heavy installations and the mixing time must be long enough to guarantee a complete melting of the ice. The technique of liquid nitrogen injection in the concrete mixer is also interesting, but it is seldom used because it is very expensive and technically complicated.

Other measures are related to the design and the construction on site. It is thus possible to avoid concrete setting of critical structural elements during strong heats or to choose a night period to minimize the temperature of the fresh concrete. Sometimes, it is also possible to modify the design of massive parts and to transform them into hollow elements which warm up much less. For the elements having great dimension, it is possible to split the concrete setting in several phases in order to increase the thermal exchanges; this splitting is effective only if a sufficient delay (at least one week) is respected between the successive pours.

Finally, it is also possible to call upon a technique of cooling used in the construction of the dams which consists in the cooling of the concrete after its pouring by incorporating coils in the concrete and by circulating fresh water inside these coils in order to evacuate the calories released by the concrete. However, to apply this method, the design and the calculation of the cooling system must be well done in order to avoid the appearance of heat gradients inside the concrete mass, in particular in the vicinity of the coils, these gradients being able to generate internal cracking.

Controlling the heating treatment of precast elements

The heating treatment of the precast elements is carried out by means of an external supply of heat in order to reduce the duration of the immobilization of the production activities, to increase the number of daily manufacture, and to get the concrete sufficient mechanical strength to operate the demoulding, the handling, or the relaxation of the prestressing strands.

A cycle of heat treatment generally comprises four phases: the phase of pretreatment, the phase of temperature rise, the phase of maintenance of the temperature, and the phase of cooling. The phase of temperature rise must be controlled so that the rate of rise remains lower than a maximum rate which is a function of «the maximum curing radius» Re_{max} (defined as the shortest distance between the points located on the axis of symmetry of the element and the exposed faces [15]). The duration of the stage of the temperature maintenance depends on the latter; this duration generally lies between 1 and 3 hours at 85 °C, and between 4 and 12 hours at 65 °C. On the normative level, the standard NF EN 13369 specifies the maximum temperature of the concrete as a function of the environment to which the precast element will be exposed.

3.5 Performance testing

A performance test on concrete cores was developed by LCPC [16 and 18]. It consists in the characterization of the risk of swelling 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:

- manufacture of concrete;
- heat treatment simulating the heating of the concrete;
- cycles of drying and humidification;
- finally, immersion in water of 20 °C and monitoring of 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*
- the 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 the 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 %.

3.6 Estimation of the temperature reached in the structures

In order to be able to apply the strategy of prevention previously defined, it is necessary to be able to consider the maximum temperature likely to be reached by the concrete within the heart of the structures. Appendix 4 of the LCPC recommendations [15] provides a method to estimate the maximum temperature reached in a concrete element for which one knows only the thickness (in its smaller dimension) and the few following basic data on the composition of the concrete:

- cement content of the concrete C
- mineral addition content A
- concrete density M_v
- effective water content E_{eff} of the concrete
- compressive strength of the cement at 2 days Rc2 according to NF EN 196-1
- compressive strength of the cement at 28 days Rc28 according to NF EN 196-1
- heat of hydration of the cement at 41 hours Q41 (in kJ/kg) according to NF EN 196-9

Finally, if one wishes to obtain a more precise estimate of the maximum temperature reached within the concrete, it is advisable to have access to a finite elements program and to take into account the heat released by the concrete from measurements of released heat according to time (calorimetric test). This heat can be deduced from the measurements of heat taken on standardized mortar («cement» test), be measured on MBE (mortar equivalent to concrete) or directly on concrete.

4 CONCLUSIONS

The internal sulphate reaction due to delayed ettringite formation has been discovered about twenty years ago in some precast elements subjected to heating, and it was only about ten years ago that it was recognized to affect structures cast in place whose concrete has reached high temperature. This rather recent discovery explains the small number of studies and research devoted to this problem until now.

Regarding prevention, it is advisable to note the important work undertaken by the LCPC with the assistance of the cement industry and the civil engineering companies to develop recommendations intended to avoid the occurrence of new disorders, and this 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. Rendez-vous will be given in ten years to evaluate if this strategy of prevention has achieved its goals.

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6 STANDARDS

NF EN 197-1 Ciment – Partie 1: Composition, spécifications et critères de conformité des ciments courants.

NF EN 206-1 Béton – Partie 1: spécification, performances, production et conformité

EN 13230-1 Applications ferroviaires – Voie – Traverses et supports en béton – Partie 1: Prescriptions générales.

NF EN 13369 Règles communes pour les produits préfabriqués en béton.

NF P15-319 Liants hydrauliques – Ciments pour travaux en eaux à haute teneur en sulfates.

TABLE 1 – Comparative Study of the various determining factors of the DEF found in appraised bridges

	Bridge « A »	**Bridge « B »**	**Bridge « C »**	**Bridge « D »**	**Bridge « E »**	**Bridge « F »**	**Bridge « G »**	**Bridge « H »**
Year of construction	**1955**	**1967**	**1980**	**1988**	**1990**	**1982**	**1988**	**1989**
Part of the bridge concerned	Crossbeam	Pier	Crossbeam	Pier	Pier	Crossbeam	Pier socket	Crossbeam
Parameters related to the temperature: • T max (°C) • concreting period	 > 80 august	 > 80 unknown	 > 80 august / sept.	 > 75 july/ august	 > 80 august / sept.	 > 70 july / august	 > 75 july / august	 > 75 july / august
Parameters related to the cement: • Cement type • SO_3 (% mass) • C_3A (% mass)	OPC 2,5 11,2	PCC[2] (10% of slag) 2,7 9,6	OPC 55R 2,6 9,8	PCC[2] 55 (10% of calcareous filler) 2,5 7,0	OPC 55R 2,8 8,2	OPC 3,2 11,0	OPC 2,2 7,1	OPC 55R 3,5 10,1
Parameters related to the concrete: • Cement content (kg/m³) • W/C ratio • Nature of aggregates • Alcali content (equivalent Na_2O kg/m³) [1]	430 0,50 Siliceous 2,0	430 0,50 Siliceous 4,3	400 0,47 silico-calcareous 4,0	380 0,54 Siliceous 4,1	410 0,46 Siliceous 2,3	350 0,49 Silico-calcareous 3,0	385 0,48 Siliceous 3,9	400 0,50 Silico-calcareous 4,6
Parameters related to the environment: • Humidity	Water-proofing problem	Lack of drainage	Condensa-tion Alternation of humidity and drying	Tidal range	Tidal range	Exposed to the elements	Exposed to the elements	Lack of drainage

[1] *Equivalent Na_2O = wt% (Na_2O + 0,658 K_2O)*
[2] *PCC: Portland Composite Cement*

TABLE 2: 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

TABLE 3: Environmental classes of a structural part with respect to DEF

Designation of the 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 durable 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 concrete structure regularly exposed to sprayed water

TABLE 4: Choice of the level of prevention

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

TABLE 5 – Presentation of the six conditions usable when the temperature threshold is exceeded

Condition 1	**Condition 2**	**Condition 3**
- Duration of the maintenance of the concrete temperature above 75°C < 4 hours for Bs and above 70°C < 4 hours for Cs - Equivalent active alkalis of the concrete < 3 kg/m^3	- Use of a cement conforming to the standard NF P 15-319 (ES). In the case of use of CEM I and CEM II/A: Equivalent active alkalis of the concrete < 3 kg/m^3	- Use of cements non conforming to the standard NF P 15-319 of the type CEM II/B-V or CEM II/B-S or CEM II/B-Q or CEM II/B (S-V) or CEM III/A or CEM V - With SO_3 of cement < 3 % and C_3A of the clinker < 8 %

Condition 4	**Condition 5**	**Condition 6**
- Use of fly ashes, slags, or calcinated natural pozzolans, in combination with a CEM I, - Additions content > 20 % - With SO_3 of cement < 3 % and C_3A of the clinker < 8 %	- Checking of the durability of the concrete with respect to DEF, by mean of the performance test and by satisfying the criteria	- For precast elements, the couple concrete/foresight heating is identical or similar to a couple concrete/heating having at least 5 references of use without any problem