EXPERIENCE IN LIMITING EARLY AGE CONCRETE TEMPERATURE FOR DEF PREVENTION

François Cussigh (1)

(1) VINCI Construction France

Abstract

High temperature concrete curing has always been a concern for concrete construction, first for preventing thermal cracking and more recently to impede delayed ettringite formation. In 2007, French recommendations for DEF prevention have been published with different prevention levels defined with the care of ensuring in the same time a proper control of DEF risks and practical possibilities to use mass concrete in civil engineering projects. This paper describes how early-age concrete temperature has been kept under control on different civil engineering projects during the last 20 years, focusing on recent projects on which precise limits for peak temperature have been included in concrete technical specifications of the construction contract. The use of blended cement (fly ash, blast furnace slag, etc.) has proved to be helpful for allowing at the same time higher peak temperature and reduced heat development. This is a new option for civil engineering concrete (historically CEM I was the preferred option) and technical specifications should be updated to favour that option.

Résumé

La limitation de l’élévation de température au sein du béton a toujours été une règle à respecter, dans un premier temps pour éviter la fissuration de retrait thermique et plus récemment pour prévenir les risques de réaction sulfatique interne. En 2007, les Recommandations françaises pour la prévention de la RSI ont été publiées avec différents niveaux de prévention dans le souci à la fois de maîtriser les risques liés à la RSI mais aussi de préserver la possibilité pratique de construire des pièces massives en béton. Cet article décrit comment l’élévation de température du béton au jeune âge a été maîtrisée sur différents projets de génie civil de ces vingt dernières années, et plus particulièrement sur les projets récents pour lesquels des limites de température maximale ont été intégrées aux spécifications techniques. L’utilisation de liant composé (avec cendres volantes, laitier de haut fourneau,…) s’est révélée utile à la fois pour augmenter le seuil de température admissible et pour réduire la chaleur d’hydratation du béton. Cette option n’est pas classique pour les ouvrages de génie civil (le CEM I a longtemps été le choix privilégié) et les spécifications techniques doivent évoluer pour les favoriser.
1. INTRODUCTION

High temperature concrete curing has always been a concern for concrete construction even when delayed ettringite formation was not clearly identified as a threat for concrete durability (before 21st century). Limitation of concrete peak temperature was recommended in order to avoid cracking (from thermal shrinkage stresses) and not to alter long term mechanical performance.

Precise limits for DEF prevention have been defined in 2007 through French Recommendations published by LCPC: “Recommandations pour la prévention des désordres liés à la réaction sulfatique interne” [1]. Several civil engineering projects have been conducted since then; mass concrete pours have been justified and controlled according to those recommendations. This paper presents different applications illustrating how early age concrete temperature can be kept under control.

2. FRENCH RECOMMANDATIONS

The French recommendations were built taking into account the multiple parameters involved in the delayed ettringite formation phenomenon in terms of concrete curing temperature history and concrete mix design. As for alkali-silica reaction, different prevention levels were defined with the care of ensuring at the same time a proper control of DEF risks and practical possibilities to use concrete in civil engineering projects (too strong requirements with limited freedom degrees could have been a brake put on concrete construction).

3. APPLICATIONS

Here below applications are presented in chronological order.

3.1 Normandy bridge (1991)

The pylon bases, 3.5 m thick (about 1200 m³ of concrete), were cast in one go by using a moderate heat concrete with strength class C40/50 and without any specific requirement for early-age strength. In order to limit heat development, cement dosage was reduced from 400 to 375 kg/m³ with an accepted relaxation of the initial specifications. Blended cement (CEM II) with slag was used for this concrete.

Temperature was recorded on every of the four pylon bases. In Figure 1 an example from one of the casting phases is displayed.

The maximum peak temperature recorded was 70 °C in October 1991. The main concern was about temperature differential and early-age thermal cracking risks.
3.2 CTRL Medway bridge (1999)

The pile caps, up to 5 m thick, were cast in one go by using a low heat concrete with high slag content (120 kg/m$^3$ of Portland cement and 280 kg/m$^3$ of slag) with strength class C30/37 and without any specific requirement for early-age strength.

The pier lifts were massive because of a plain section of 2m x 5m, with C50/60 concrete class. Due to climbing formwork method, early-age strength requirement of 10 MPa at 20 hours has been specified. The mix used contained 210 kg/m$^3$ of Portland cement and 210 kg/m$^3$ of ground granulated blast furnace slag. Recorded peak temperature reached up to 75 °C during July 1999. Once again, there was no precise limit but thermal differential values were kept under control in order to prevent early-age cracking.

3.3 Aquitaine bridge (2001-2002)

Anchorage beams for renewed suspension cables were designed with C60/75 concrete for mass pours. Those beams have been cast in a series of successive lifts with dimensions 30 m x 4 m x 2.5 m. Due to those dimensions, numerical thermal simulations were performed in order to check the ability of the designed reinforcement to control cracks opening taking into account a mix design made of 400 kg/m$^3$ of CEM I 52,5 (Portland cement) and 30 kg/m$^3$ of silica fume. It was then highlighted that peak temperature could reach 68 °C with a fresh concrete temperature of 20 °C. Because fresh concrete temperature was likely to exceed 25 °C when casting during summer time, it was then necessary to define suitable means of controlling concrete peak temperature, either by modifying concrete mix design or by cooling means.
Because it was not allowed to change concrete mix design (the client didn’t give his agreement) and despite significantly improved results obtained with alternative mixes, it was decided to limit early-age concrete temperature (maximum allowed temperature was set equal to 70 °C) through concreting by night and using internal cooling during the first hours after casting. A dense network of plastic cooling pipes (diameter 25 mm) was installed inside the reinforcement frame, with typical interval between pipes of 400 mm (this operation was difficult due to high density of reinforcement). About 5 hours after end of casting, fresh water from public network was being circulated at high speed through the plastic pipes in order to cool down concrete mass. Due to excessive concrete heat development (about 310 J/g of binder), it was not possible to control heat exchange: water flow rate was set at maximum level but water temperature differential between inlet and outlet points was typically 20°C (the objective was to limit this differential value under 4 °C). As indicated in Figure 2, internal cooling has reduced peak temperature by about 10 °C but a proper control of concrete temperature was not obtained. It was calculated that the lack of balance between concrete heat development and cooling power was such that cooling was only efficient at the end of concrete heat development: maximum concrete heat flow was about 12000 kJ/h/m³ while cooling power maximum value was about 2000 kJ/h/m³. That’s why this job site experience was a demonstration that internal cooling shouldn’t be used without taking care of limiting concrete heat development by optimizing concrete mix design.

![Figure 2: Temperature recording in Aquitaine bridge beams](image-url)
3.4 Beauvais Bridge (2006)

The Beauvais Bridge (across A16 highway) was one of the first civil engineering projects on which French Recommendations published by LCPC: “Recommandations pour la prévention des désordres liés à la réaction sulfatique interne” [1] have been used as reference for concrete specifications. As high performance concrete was required for pylon and deck, a special mix design was developed based on slag cement CEM III/A 42,5 N with 57 % clinker and 43 % slag.

Once again, a relaxation was necessary because technical specifications were specifying the use of high clinker content cement type CEM I or CEM II/A (S or D) although mass pours were necessary for the following concrete parts:

- Mobile part of the deck : 4 m thick
- Pylon bases : 3.5 m thick (see Photo 1 here below)
- Pylon head : 2.2 m thick

The final mix was adjusted with 385 kg/m³ of cement CEM III using a new generation superplasticizer admixture in order to get a water-to-cement ratio of 0.42 with high fluidity and satisfying pumping behaviour despite of the use of 100 % crushed aggregates. The change from CEM I to CEM III allowed a peak temperature reduction of 13 °C. During the trial mixes, a mock-up was cast (dimensions 2 m x 2 m x 4 m) in order to check temperature evolution within the concrete element, in two successive lifts 2 m high cast on two successive days (28 and 29 June 2006).
Maximum allowed temperature was defined depending on prevention level Cs and concrete binder type (low sulphate and C₃A clinker with more than 20 % of slag): 80 °C. Numerical simulations for the different mass pours were performed after checking input data from mock-up experience. It was deduced that maximum allowed fresh concrete temperature was between 27 °C and 29 °C depending on the cases, which was quite compatible with local climate in Beauvais. Concrete temperature was monitored during construction phases and results obtained were according to initial calculations (Figure 3).

![Mock-up](image)

Figure 3: Temperature recording in Beauvais bridge mock-up

### 3.5 Fos harbour dock 2XL (2008-2009)

Concrete class C45/55 for crowning beam (section 2.3 m x 4.6 m) had at the same time to ensure sufficient durability (100 years) in marine environment (resistance to chloride ingress) and prevent delayed ettringite formation. Contract specifications were specifying concrete made of 385 kg/m³ of CEM I or CEM II, a mix design with 320 kg/m³ of CEM I 52,5 N PM ES and 80 kg/m³ of fly ash from local thermal plant was proposed and validated through durability indicators measurement (performance-based approach). In terms of resistance to chloride ingress, the proposed mix design showed very good results thanks to low water by binder ratio and fly ash contribution.

Fly ash incorporation was also useful for heat control and first calculations made using simplified method given in annex IV of French recommendations [1] gave a maximum peak temperature of 66 °C with 20 °C fresh concrete temperature. During the trial mixes, temperature monitoring on mock-up made of 1 m-side insulated cube was used to check input
data for numerical thermal simulation and the calculated peak temperature deduced from simulation for the crowning beam casting was 67 °C for 20 °C fresh concrete temperature (very close to initial calculation with simplified method).

Maximum allowed temperature was defined depending on prevention level Cs and concrete binder type (low sulphate and C₃A Portland cement with 20% of fly ash): 80 °C. Therefore, as expected fresh concrete temperature during summer time was 30°C, maximum expected peak temperature was 77 °C and complied with DEF prevention requirements.

3.6 La Cotière Viaduct (2009-2010)

For La Cotière viaduct near Lyon, the pier lifts and pier caps were 5 m and 4.5 m thick as shown on Figure 4. The main difficulty for concrete mix design optimization was at the same time to limit peak temperature and to reach sufficient early-age strength in order to cast successive pier lifts without any delay for climbing formwork platform. For this last point, a minimum compressive strength of 10 MPa at 18 hours was specified.

The C35/45 mix design was optimized with 320 kg/m³ of CEM I 52,5 N PM ES and 80 kg/m³ of fly ash. The choice was made in order on the one hand to benefit from higher limit for peak temperature and on the other hand to lower concrete heat development. First calculations made using simplified method given in annex IV of French recommendations [1] gave a maximum peak temperature of 73 °C with 30 °C fresh concrete temperature (summer conditions), while maximum allowed temperature according to prevention level Cs was 80°C. Then, numerical thermal calculations were performed with input data from heat development measurement on concrete binder and gave similar value: 74°C with 30°C fresh concrete temperature. Final mix design was validated based upon those calculations. Maximum peak temperatures were recorded on pier cap P11 and P12 cast in June 18th and July 2nd, 2009 (Table 1)

Figure 4: Geometry of La Cotière viaduct piers
3.7 Bacalan bridge (2011)

On Bacalan bridge, located in Bordeaux, most critical concrete parts for DEF prevention are pier lifts of P1 and P4 because of their plain section (3 m thick) and also because, due to global construction time schedule, it was absolutely necessary to get an early-age strength of 10 MPa at 15 hours. The first mix design used, for pier P1, was made of 340 kg/m³ of CEM II/A-S 52,5 N PM and 85 kg/m³ of metakaolin, introduced in order to decrease heat development and allow higher peak temperature. Due to very hot temperature conditions in April 2011 and despite water spraying on coarse aggregates and the use of cold water for concrete batching, fresh concrete temperature reached up to 30 °C (which was unexpected for that given period of casting) and the mix designed had to be modified with 310 kg/m³ of CEM II/A-S 52,5 N PM and 80 kg/m³ of metakaolin. This change didn’t exhibit sufficient reduction of concrete heat development through temperature recording of a mock-up cast during trial mixes and it was finally decided to change binder type and use for P4 casting (during May and June 2011) concrete made of CEM III/A 42,5 N PM ES containing 70 % of slag. In order to match early-age compressive strength specification, hot water was used when necessary to ensure a fresh concrete temperature at least equal to 25 °C. Due to very low heat cement use, temperature increase was about 35 °C.

4. CONCLUSIONS

The French recommendations for DEF prevention are leading for mass pours, most of the time, to the choice of suitable binder type in order to allow increased peak temperature (65 °C or even 70 °C limits are quite impossible to comply with) and to lower concrete heat development.

Optimization of concrete mix design is the key parameter for DEF prevention but it is of course necessary to keep fresh concrete temperature under control. This is sometimes difficult because French climate can undergo significant variations during intermediate seasons and concrete batching plants of ready-mix network are not equipped with cooling means.

Generally, internal cooling is not necessary if concrete mix design is optimized taking into account realistic fresh concrete temperature with sufficient safety margin.

REFERENCES