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Using the maturity method in concrete cracking control at early ages

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Abstract

The maturity method based on the Arrhenius law makes it possible to predict the concrete's compressive strength evolution in a structure on the basis of a 20 °C characterization. This technique has been successfully used and improved now for more than 20 years. Examples are mentioned in this paper. The recent French National Project CALIBE (for "quality of concrete") produced a handbook that synthesizes the improvement of the 20 years on site experience of the technique and shows the way to use the maturity method in a conservative way to predict the concrete's compressive strength in situ.

This technique can also be applied successfully to predict the characteristics (Young's modulus, tensile strength, thermal coefficient) needed to control the risk of cracking in cement based materials through the use of numerical tools such as the finite element program CESAR-LCPC.

Keywords: Concrete; Cracking; Risk control; Maturity method; Recommendations; Prediction; Numerical tools; CESAR-LCPC; Finite element model; On site experience

1. Introduction

While hardening, a concrete structure is exposed to a risk of cracking. There are several levels of cracks. Some cracks are less harmful from a mechanical point of view (even if they are always more or less prejudicial to durability), either because they appear on freshly-placed concrete (related to the plastic shrinkage) or because they will later be filled (less than 0.12–0.2 mm) or because they do not represent a risk for the structure (map cracking).

As regards the harmful cracks, they can have several origins [1]:

- temperature, with its direct or indirect effects,
- autogeneous or drying shrinkage,
- degradation of the concrete (alkali-aggregate reaction, freezing effects etc...).

This paper focuses on the cases for which a proper preliminary characterization of the concrete at early ages makes it possible to estimate the risk of cracking, and thus to limit it through a possible corrective action on the mix design or the building process.

1.1. Cracks and shrinkage

The hydration of cement generates heat which causes an increase of the temperature of the concrete. When the surface of the concrete loses heat to the atmosphere, a difference of temperature appears between the cold outside and the hot centre of the element. It results from it that free thermal dilation is not the same in various parts of the concrete element. If the tensile stress on the surface of the element, due to dilation in the centre, exceeds the tensile strength of the concrete or if it causes an overshooting of tensile deformation capacity, a crack on the surface appears. Nevertheless, the creep capacity of the concrete, which is very significant at early ages, can relieve part of the compressive stresses induced in the centre. Thermal strain is not the only cause of superficial cracking. It may also be due to drying shrinkage of the surface of the concrete structure.

Cracks can also occur during the concrete's cooling phase. When the concrete is in contact with a surface whose temperature is even lower, such as cold ground or

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a non-insulated formwork in cold weather, the concrete setting in different parts of the element is carried out at different temperatures. Consequently when the centre of the concrete element cools, its thermal contraction is obstructed by the already cooled and relatively stiff external part and cracking can occur inside the concrete. It is again a form of internal restraint which leads to cracking.

At a larger scale, an external restraint to global shrinkage (either autogeneous or thermal) of the structure can also cause cracking of the reinforced concrete elements (e.g.: a wall poured onto an existing concrete foundation).

1.2. Others aspects to be considered

The potential for shrinkage related cracking depends not only on the applied strains contraction but also on the cracking strain or extensibility of the concrete, its tensile strength and on the degree of restraint against the deformation which can create cracking.

Thus time has a double effect: on the one hand, it permits an increase in the strength of the concrete, which reduces the risk of cracking, but on the other hand, the modulus of elasticity also increases so that the stress induced by the given shrinkage becomes more significant. Moreover, the relaxation of creep capacity decreases with the age so that the tendency to cracking becomes more significant.

In summary, strong gradients of temperature or moisture or the restraint of free movement at a boundary of a structural element may involve a high cracking tendency.

1.3. Usefulness of the maturity method

It is possible to limit the risk of cracking by modifying the concrete mix as well as the casting conditions; for example to insulate the formwork to limit the heat gradients inside a massive concrete structure, or not to put in place prestress or not to move precast elements before the concrete has reached a sufficient compressive strength. For that, it is necessary to know the evolution of the concrete characteristics after casting.

It is then that the maturity method takes all its importance. Indeed, the maturity method consists, from forecasts or measurements of temperature in a work, to determine by calculation the degree of advancement of the hydration reactions corresponding to the concrete hardening. The concept of maturity makes it thus possible to estimate the maturity state of the concrete, i.e. its level of hardening, which is related to every characteristic of the concrete.

Before the commencement of a concrete project, it is possible, using numerical tools, to determine if the casting conditions provided for will be sufficient to limit the cracking risks. If not, one or several casting conditions may be changed to limit cracking. Once on construction site, when castings have started, it is possible, using temperature measurements in various critical points of the work, to deduce the evolution of intrinsic parameters of the concrete and thus to predict the risk of cracking.

2. The maturity method to predict the concrete early-age compressive strength

2.1. Theoretical basis

The concrete hydration is a time and temperature-dependant process. At a given age (since mixing) the strength of a concrete depends on the concrete thermal history. The age is thus not sufficient to estimate the strength. The concept of maturity was introduced to describe the level of development of the hydration process of a concrete. To a given maturity corresponds a given level of the concrete characteristics and particularly a given compressive strength, as expressed in the Saul “maturity law” [2]: “Samples of the same concrete will have equal strength if they have equal maturity, irrespective of their actual time-temperature histories.”

The maturity is usually calculated as follows:

$$M(t,H(T)) = \int_0^t K(T(\tau))\,\mathrm{d}\tau \tag{1}$$

where $M(t,H(T))$ is the maturity at age t after temperature history $H(T)$; $H(T)$ is the temperature history $T(\tau)$, τ varying from 0 to actual age t; $K(T)$ is the rate function which is dependent on the temperature T of the concrete.

The equivalent age concept was introduced later [3,4]. For a concrete having a given maturity after a given temperature history, it is defined as the time during which the concrete should be placed at a reference constant temperature (usually 20 °C) to reach the same level of maturity. Mathematically, we have:

$$M(t,H(T)) = M(t_{\mathrm{eq}}, T_{\mathrm{réf}}) \tag{2}$$

where $M(t_{\mathrm{eq}}, T_{\mathrm{réf}})$ is the maturity at age t_{eq} at constant temperature $T_{\mathrm{réf}}$; t_{eq} is the equivalent age.

Eqs. (1) and (2) give:

$$\int_0^t K(T(\tau))\,\mathrm{d}\tau = \int_0^{t_{\mathrm{eq}}} K(T_{\mathrm{réf}})\,\mathrm{d}\tau \tag{3}$$

But:

$$\int_0^{t_{\mathrm{eq}}} K(T_{\mathrm{réf}})\,\mathrm{d}\tau = K(T_{\mathrm{réf}}) \cdot \left(\int_0^{t_{\mathrm{eq}}} \mathrm{d}\tau \right) = K(T_{\mathrm{réf}}) \cdot t_{\mathrm{eq}} \tag{4}$$

From (3) and (4) we have thus:

$$t_{eq} = \int_0^t \frac{K(T(\tau))}{K(T_{réf})} \, d\tau \tag{5}$$

The Arrhenius law is generally accepted [5–7] as the most suitable rate function for concrete:

$$K(T) = A \cdot \exp\left(-\frac{E_a}{R \cdot T}\right) \tag{6}$$

where E_a is the apparent activation energy of the hydration process (in J/mol); T is the absolute temperature (in K); R is the universal gas constant (8.314 J/mol K); A is the constant of the rate function.

The associated equivalent age function is then:

$$t_{eq} = \int_0^t \frac{K(T(\tau))}{K(T_{réf})} \, d\tau = \int_0^t \exp\left[\frac{E_a}{R}\left(\frac{1}{T_{réf}} - \frac{1}{T(\tau)}\right)\right] d\tau \tag{7}$$

The success of the Arrhenius law was far from being predictable since the hydration process is not a single pure chemical reaction for which this law is usually suitable. Nevertheless, it is not the first time that this famous law has proved to be adequate to describe complex chemical reactions.

2.2. Practical application of the maturity method

In practice, the maturity method involves three phases [8]:

- *A calibration phase:* This consists of measuring the evolution of the compressive strength of the concrete at the beginning of the project (around the expected strength values needed on different critical points of the structure) when submitted to different temperature conditions, which are as close as possible to the expected extreme concrete temperatures on the project, and in finding the apparent activation energy which explains the observed differences of the kinetics of strength increase for the chosen temperature conditions; this phase leads also to the development of the "concrete calibration curve" i.e. the curve giving the evolution of the concrete compressive strength vs. time at 20 °C, deduced from the previous results (including a safety margin).
- *A validation phase:* This occurs during the first weeks of the project; it makes it possible to check that the variations in the characteristics of the concrete constituents do not have too much influence on the concrete characteristics obtained in the calibration phase (calibration curve and apparent activation energy); at the end of this phase, the "calibration curve" becomes the "reference curve" and can be used on the project.
- *An on site application phase:* This continues throughout the project and includes regular checking of the characteristics.

The limits of the theory mentioned earlier may lead to a relatively high safety margin in the calibration phase, which results in a high "safety cost" for the user. Thus, the narrower the temperature and the strength tested ranges in this phase, the more accurate the strength estimation and the lower the "safety cost". Provided that the guidelines in Ref. [8] are followed, the use of the maturity method is perfectly suitable to predict on site concrete strength evolution with a reasonable accuracy.

2.3. The on site use of the maturity method: a 20 years experience

Maturity method has been used for more than 20 years in Europe on many different projects, mainly for assessing the early-age compressive strength of concrete [9,10].

Some examples are given here below:

- precast segments of "Ile de Ré" bridge (1987)
- pylons and deck segments of Normandy bridge (1991)
- "Pas de l'Escalette" tunnels A75 (1994) [11]
- cantilever deck segments of Rhone Viaduct BPNL (1994)
- cooling towers of Civaux nuclear plant (1994)
- Rochecardon and Duchère tunnels BPNL (1995)
- Montjézieu tunnels A75 (1995)
- Mirville viaduct A29 (1995)
- Amiens PI4 viaduct (1995)
- TGV viaducts in Avignon (1997)
- Cut and cover in Taverny A115 (1997)
- Nièvre viaduct A16 (1998)
- Lisieux PI5 viaduct (1998)
- Channel tunnel rail link, Medway bridge (2000)

On the Normandy bridge site, maturity meters have been widely used for many parts of the structure cast with high performance concrete (B60 with silica fume) showing very good early-age strength performance (see Fig. 1). More especially, for the cantilever deck segments, and the launched deck segments of this project, each prestressing operation was authorized after checking the concrete maturity just behind the anchorage and deducing the early-age compressive strength value. The required strength varied between 12 and 35 MPa. No problem of concrete cracking in the anchorage zone due to insufficient concrete strength when stressing the cables was recorded after 25,000 m^3 of tested concrete (corresponding to 84 cantilever elements and 177 launched deck elements). Maturity meters were used instead of concrete cylinders, which are not sufficiently

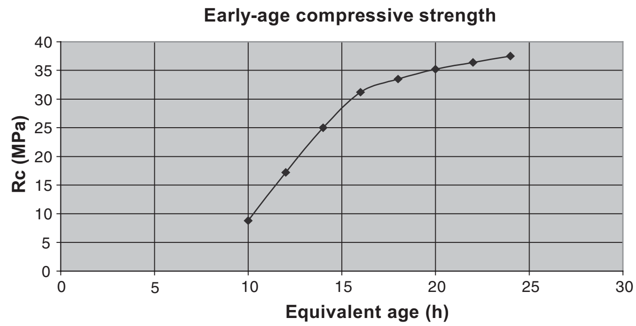


Fig. 1. Normandy bridge high performance concrete early-age strength vs. equivalent age (at 20 °C).

representative of true in situ strength, allowing a good optimization of production cycles without risks in terms of job site safety or concrete cracking.

This project and the many others mentioned above are proof that the maturity method is presently the more accurate system for determining in situ concrete strength.

As there is no national standard in France for maturity-method application, and in order to harmonize the different existing systems (maturity meters, software, temperature probes, calibration including apparent activation energy determination), a guide has been prepared within the scope of the National Project CALIBE [8]. This guide gives precise instructions for calibration and definition of safety margins applied to early-age compressive strength. In comparison, the ASTM standard C 1074 [12] does not impose a calibration on concrete (the use of a modified mortar is recommended) and laws others than Arrhenius law are proposed as rate function for concrete.

In some cases, more especially for mass concrete, maturity-method principles have been used for predicting the temperature distribution in the concrete elements. An example related to the Aquitaine bridge project (in Bordeaux, still on going in 2002) where large beams (30 m × 4 m × 3m) have to be cast with high performance concrete (B60). Several concrete mixes were compared in the laboratory by measuring the heat development in a Langavant insulated bottle. The mixes had the same 28-day compressive strengths and generate similar total heat but can lead to very different temperature distribution inside concrete elements.

To illustrate the effect of such differences, two numerical simulations for a simple wall measuring 10 m × 3 m × 1 m were made with two of the concrete mixes tested for the Aquitaine bridge. Parameters such concrete initial temperature, boundary conditions, heat exchange coefficients were kept identical. With the two different mixes, temperature differentials are in one case of 40 °C and in the other case of 21 °C (see Figs. 2 and 3). Since it is usually admitted that the cracking risk significantly increases when the temperature differential exceeds 20 °C, this risk appears to be very different for the two indicated cases. This is due to the fact that the hydration kinetics are quite different (because admixture systems are different) and above all the Arrhenius apparent activation energy values are in one case of 25,000 J/mol and in the other case of 46,000 J/mol.

It is, therefore, absolutely necessary to describe precisely the thermal behavior of the concrete mix (adiabatic heat development but also Arrhenius apparent activation energy) before assessing the temperature distribution (versus time) in concrete elements. In such case, good correlation is observed between calculated and real temperature values, as shown on the Alsthom Belfort example, the geometry of witch is shown in Fig. 4. As it can be seen by comparing the simulated (Fig. 5) and the actual (Fig. 6) temperature rises in the structure, maturity method is able to assess with a good accuracy the temperature distribution inside concrete elements

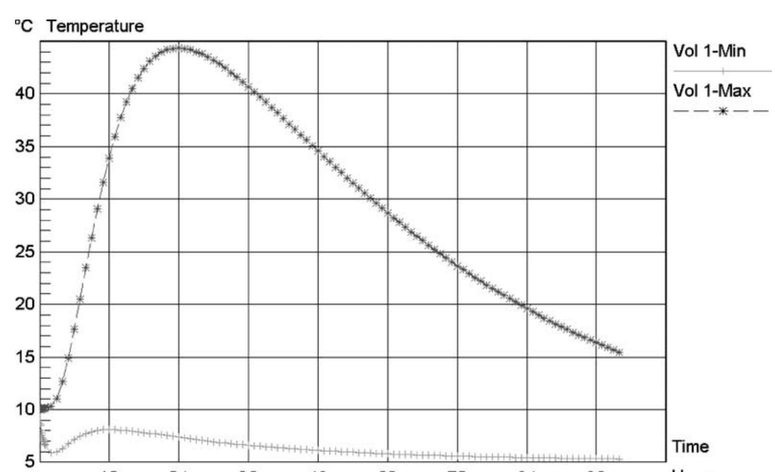


Fig. 2. Max and min temperature in a wall vs. time (concrete mix—example no. 1).

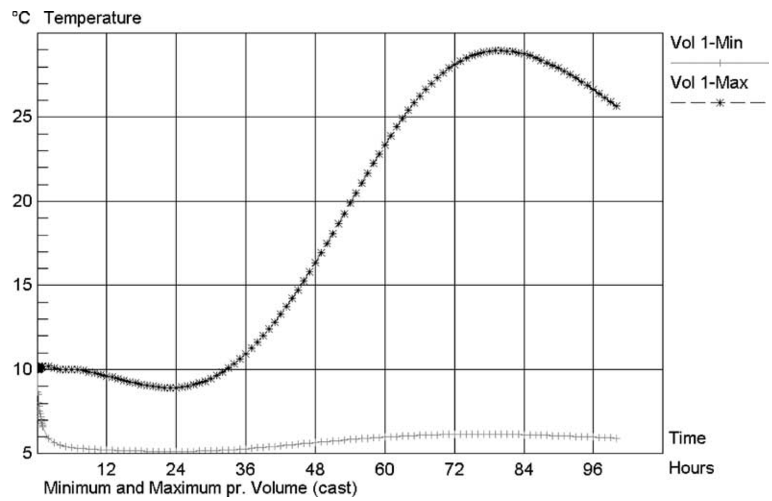


Fig. 3. Max and min temperature in a wall vs. time (concrete mix—example no. 2).

and to measure the maturity from which early-age compressive strength can be deduced.

In order to prevent thermal cracking, parameters such as Young's modulus, early-age tensile strength, relaxation due to creep should be taken in to account. Most of them can be deduced from the maturity and the next section describes numerical tools which integrate those parameters to estimate the cracking risk.

3. Estimating the cracking risk of concrete structures

The rise of temperature due to the heat of hydration of cement can be intensified by the mass effect in large concrete structures and partly modified by factors such as ambient temperature, nature and thickness of formwork. As it was stated before, temperature has a kinetic-type influence on the compressive strength development at early age. The higher the temperature, the faster the concrete strength will develop. In addition, the risk of thermal cracking occurring during cooling of the concrete, due to the combination of several factors: modulus of elasticity, restraint conditions and thermal gradients between the inside and the outside of a concrete element. Also, high temperature at early age, i.e. greater than 60–70 °C (depending mainly on the type of cement, mix design and environmental conditions), can lead to the appearance of long term chemical disorders like delayed ettringite formation (DEF).

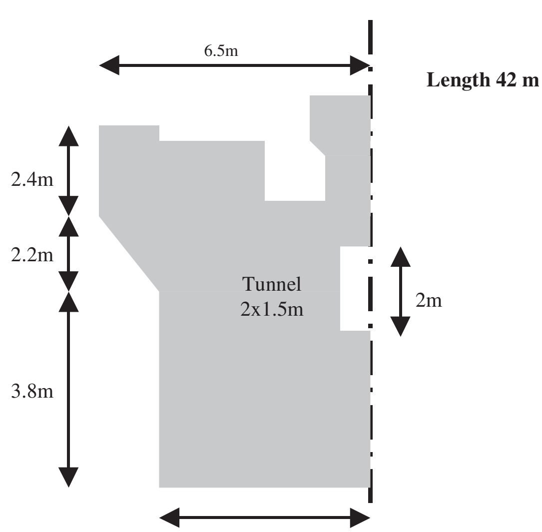


Fig. 4. Alsthom Belfort—geometry of the half tunnel.

Three types of problems can be identified to be of practical significance:

- The limitation of the in-place concrete temperature to prevent chemical disorders like DEF from appearing.
- The estimation of the in-place concrete strength in order to ensure formwork removal or safe prestressing time.
- The limitation of the induced thermal stress in order to avoid thermal cracking.

The first point is not the purpose of this paper and is mentioned here for a sake of completeness. The second one has already been dealt with in the previous section of this paper. Hence, the next section will focus only on the third point: avoidance of thermal cracking.

3.1. The use of numerical tools in combination with the method of equivalent age

A solution to avoid thermal cracking can be found by using numerical tools in combination with the "method of equivalent age" (cf. Section 2.1). A numerical tool like the finite element program (FE) CESAR-LCPC

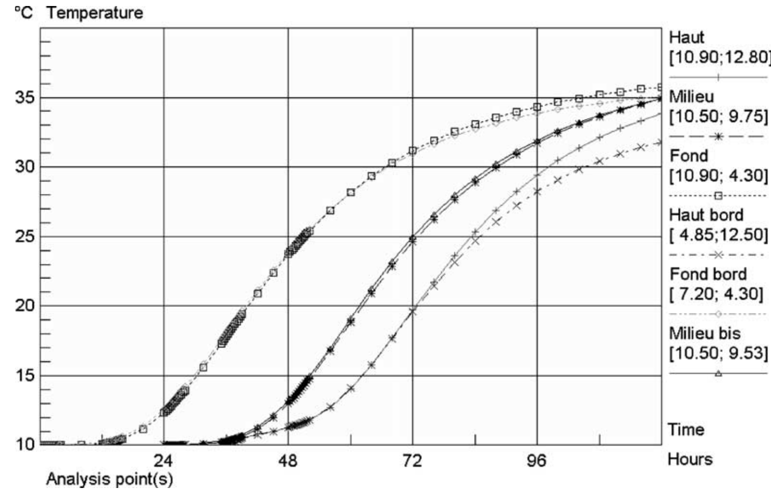


Fig. 5. Alsthom Belfort—simulated temperature rise for several points (to be compared with Fig. 6).

[13,14] allows the calculation of temperature and induced thermal stress fields in concrete structures. The risk of thermal cracking can be estimated by comparing the induced thermal stress in the structure to the tensile strength of concrete.

A correct estimation of the concrete compressive strength from actual or simulated temperature histories can be done by using the method of equivalent age (cf. Section 2.1). The concrete tensile strength can be calculated from the compressive strength on the basis of code formulae like that stated in the European Standard Eurocode 2 [15], or in the French BAEL91 and its extension [16,17]. According to these latter references:

$$\begin{cases} f_{cj} \geqslant 60 \text{ MPa} \quad f_{tj} = 0.275(f_{cj})^{2/3} \\ 40 \leqslant f_{cj} < 60 \text{ MPa} \quad f_{tj} = 0.6 + 0.06 f_{cj} \end{cases} \tag{8}$$

where f_{cj} is the compressive strength at age "j" (in MPa); f_{tj}, tensile strength at age "j" (in MPa).

It is also possible to measure directly the evolution of the tensile strength of concrete. These measurements are usually done at 20 °C. This information is not always sufficient to perform an exhaustive analyse of the risk of thermal cracking at early age. The kinetic influence of temperature on concrete strength development, especially on the tensile strength, should be also taken into account. The results presented in Section 2 of this paper indicates that the method of equivalent age could be applied to the estimation of other concrete characteristics like tensile strength or even elastic modulus.

Hence, the combination of numerical tools with the method of equivalent age enables not only to estimate the risk of thermal cracking, but also to limit it, when

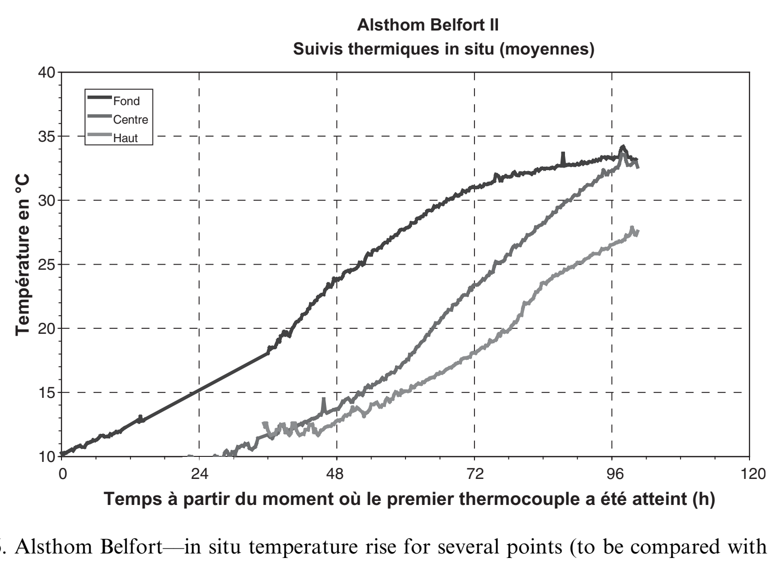


Fig. 6. Alsthom Belfort—in situ temperature rise for several points (to be compared with Fig. 5).

TEXO module

- Solution of the diffusion heat equation with a heat source:

$$\lambda \Delta T + s = \rho c \frac{\partial T}{\partial t}$$

where:

λ: thermal conductivity,

c: specific heat,

s: heat source:

$$s = \dot{\alpha}(t) Q_{\infty}$$

where $\dot{\alpha}(t)$ is the rate of hydration degree and Q_{∞} is the final heat of hydration.

- Experimental Arrhenius' law:

$$\frac{\partial \alpha}{\partial t} = f(\alpha) \exp\left(-\frac{Ea}{RT}\right)$$

where:

α: hydration degree,

T: absolute temperature, K,

R: perfect gas constant, 8.314 J/mol/K,

Ea: apparent activation energy, J/mol.

- Material characteristics and input data:

λ: thermal conductivity,
c: specific heat,
QAB test results,
Ea: apparent activation energy of concrete.

- Initial and boundary conditions:

T_{ini}: initial temperature of fresh concrete,
K: thermal exchange coefficient,
T_{amb}: ambient temperature
T_{imp}, ϕ_{imp}: imposed temperature and flow.

- Results:

Temperature field: T(t)

Hydration degree field: $\alpha(t) = \frac{q(t)}{q_{final}}$

Fig. 7. Description of the CESAR-LCPC software TEXO module.

simulations are done upstream from the casting of the structure. The tensile strength of concrete is deduced from the compressive one by using code formulae or directly estimated by applying the method of equivalent age.

3.2. The example of the finite element program CESAR-LCPC

The finite element program CESAR-LCPC [13,14] is to be more detailed in this section in order to illustrate the usefulness of numerical tools. CESAR-LCPC, has been developed by the Laboratoire Central des Ponts et Chaussées (LCPC) for more than 15 years [19,20]. The TEXO and MEXO modules of CESAR-LCPC enable the simulation of the temperature evolution and estimation of the induced thermal stress (including the stress induced by the autogeneous shrinkage) in every point of the structure.

3.2.1. Input data

Numerical tools like CESAR-LCPC, require several characteristics of the concrete as input data. For example, the specific heat c, the thermal conductivity λ, the ultimate autogeneous shrinkage β_{final}, the ultimate modulus of elasticity E_{final}, and the coefficient of thermal expansion α_{th} (constant). The apparent activation energy E_a, combined with the heat of hydration curve, enable to predict the heat of hydration development. Both these latter input data can be modelled and numerically predicted [21–25]. However, in most cases these input data are experimentally determined [18,26]. The FE Program CESAR-LCPC requires a semi-adiabatic or even adiabatic curve [27] combined with the E_a value.

3.2.2. Using CESAR-LCPC

Plane or axi-symetric 2D and 3D calculations can be made. CESAR-LCPC makes it possible for the initial and boundary conditions to be taken into account (initial temperature of fresh concrete, variable ambient or imposed temperature, initial strains and stresses). The formwork removal can be modelled with appropriate coefficients of thermal exchange. Successive calculations can be done to simulate the phasing of casting. Characteristics of the studied concrete mixture must be incorporated in the data file of CESAR-LCPC.

3.2.3. Analysing simulation results

When the tensile strength of concrete is deduced from the compressive one by using code formulae, the method of equivalent age is first used to obtain compressive strength fields from the temperature ones. Otherwise, the method of equivalent age can be directly applied to the estimation of the tensile strength.

The autogeneous shrinkage can be taken into account in the estimation of induced stress fields. If a more refined analysis is required, a supplementary study of stress relaxation due to creep (which is not included in the program at the present stage) can be followed. Stress relaxation due to creep assists into avoiding of thermal cracking by reducing the thermal stress level. Finally, the risk of thermal cracking is estimated by comparing induced thermal stress with concrete tensile strength. Induced thermal stresses can also be taken into account in the calculation of the required reinforcement.

The approach followed by CESAR-LCPC relative to the modelling and required input data, is summarised on Figs. 7–9. In the analysis, it is possible to modify the type of cement (lower heat of hydration), the age of formwork removal and the curing conditions in order to meet strength requirements at early age. The risk of thermal cracking can be also limited and taken into account in the calculation of reinforcement. Hence numerical tools combined with the method of equivalent age are used to find an optimum

MEXO module

- Aging thermo-elastic law:

$$d\varepsilon = d\varepsilon_{el} + d\varepsilon_{r} + d\varepsilon_{th} = (\alpha_{th} dT - \beta d\alpha)\mathrm{l} + \frac{1+\nu}{E(\alpha)} d\sigma - \frac{\nu}{E(\alpha)} \mathrm{trace}(d\sigma)\mathrm{l}$$

elastic contribution — autogeneous contribution — thermal contribution

- Evolution laws:

Autogeneous strain:

$$\beta(\alpha) = -\alpha\beta_{fin}$$

β_{final} is the final value of the autogeneous shrinkage estimated by the AFREM model:

$$\beta_{fin} = 1.4(2S_{c28} - 40)10^{-6}$$

S_{c28} is the 28-d compressive strength

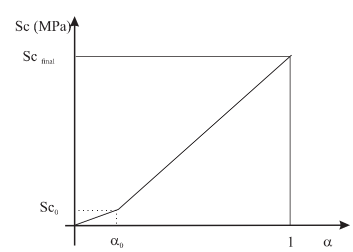
Elastic modulus:

$$E(\alpha) = E_{final}\, h(\alpha)$$

$$h(\alpha) = \frac{1 + 1.37 Sc_{final}^{2.204}}{1 + 1.37 Sc(\alpha)^{2.204}} \left(\frac{Sc(\alpha)}{Sc_{final}} \right)^{2.675}$$

$$Sc_{final} = \left(\frac{E_{final}}{7250} \right)^{\frac{1}{0.471}}$$

$$\begin{cases} \alpha \le \alpha_0, \ Sc(\alpha) = \dfrac{\alpha}{\alpha_0} Sc_0 \\ \alpha \ge \alpha_0, \ Sc(\alpha) = (Sc_{final} - Sc_0)\left(\dfrac{\alpha - \alpha_0}{1 - \alpha_0} \right) + Sc_0 \\ Sc_0 = \alpha_0 \dfrac{Sc_{final}}{10} \end{cases}$$



- Material characteristics and input data:

ν = 0.2: Poisson ratio,
α_{th}: thermal dilatation coefficient,
β_{final}: final autogeneous shrinkage,
E_{final}: final elastic modulus.

- Initial and boundary conditions:

Initial stresses,
Imposed displacements.

TEXO Results: $T(t), \alpha(t)$

- Results:

Induced thermal stress fields: $\sigma(t)$

Fig. 8. Description of the CESAR-LCPC software MEXO module.

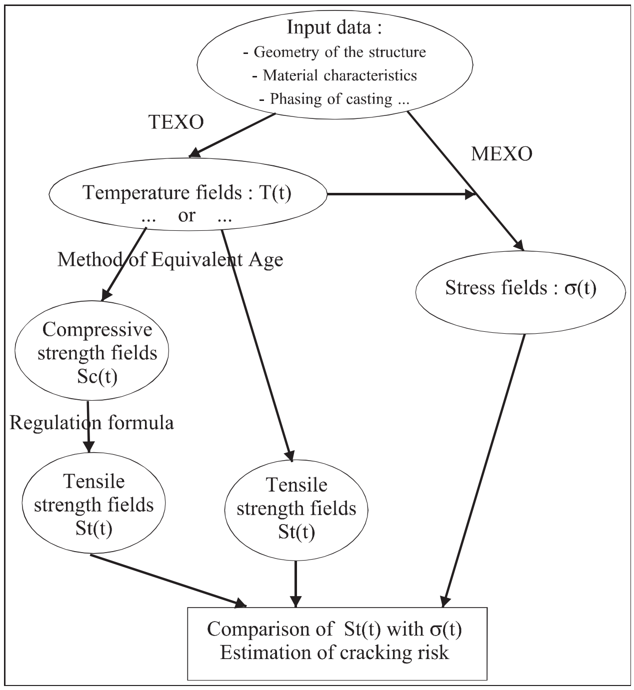


Fig. 9. The use of CESAR-LCPC in combination with the method of equivalent age.

combination of mix design, structural design and phasing of casting.

3.3. Case studies

CESAR-LCPC has been used to predict and control the temperature rise and the risk of thermal cracking on several construction sites [28,29]. A recent example is the Viaduct of Verrières (France). In this case, illustrated in Figs. 10 and 11, in situ temperature measurements were in good agreement with simulation results and led to the location of maximum tensile stress levels and to a satisfactory estimation of the cracking risk [30,31].

It must be emphasised that a correct estimation of temperature fields, mechanical strength and risk of thermal cracking depends not only on the quality of input data, but also on the relevance of modelling and on the proper description of the initial and boundary conditions.

4. Conclusions

Two decades experience has shown that the maturity method is perfectly suitable to predict in situ concrete compressive strength. This technique was extended successfully to the concrete cracking control in structures through the use of numerical tools such as finite element programs. This approach provides results which are reasonably accurate, provided that the concrete is correctly characterized and the method of the construction properly described.

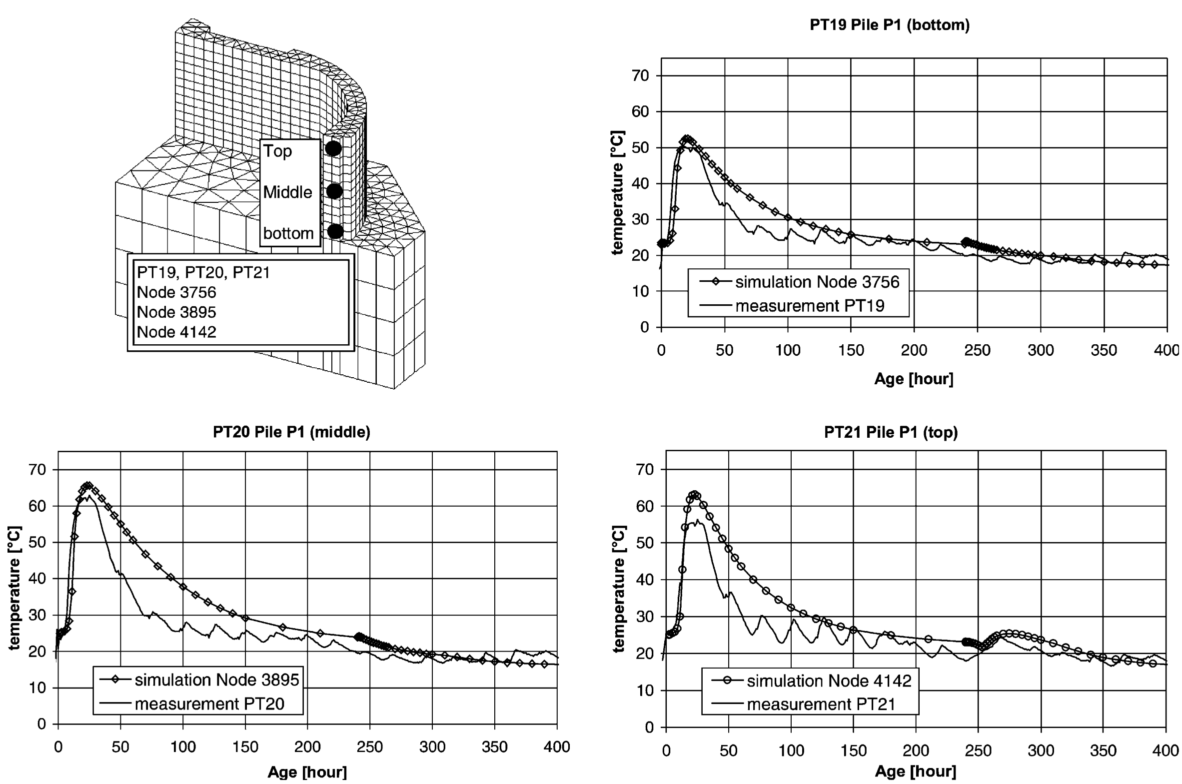


Fig. 10. Comparison of in situ temperature measurements and simulation results (Casting of pile P1—Viaduct of Verrières, France) [30].

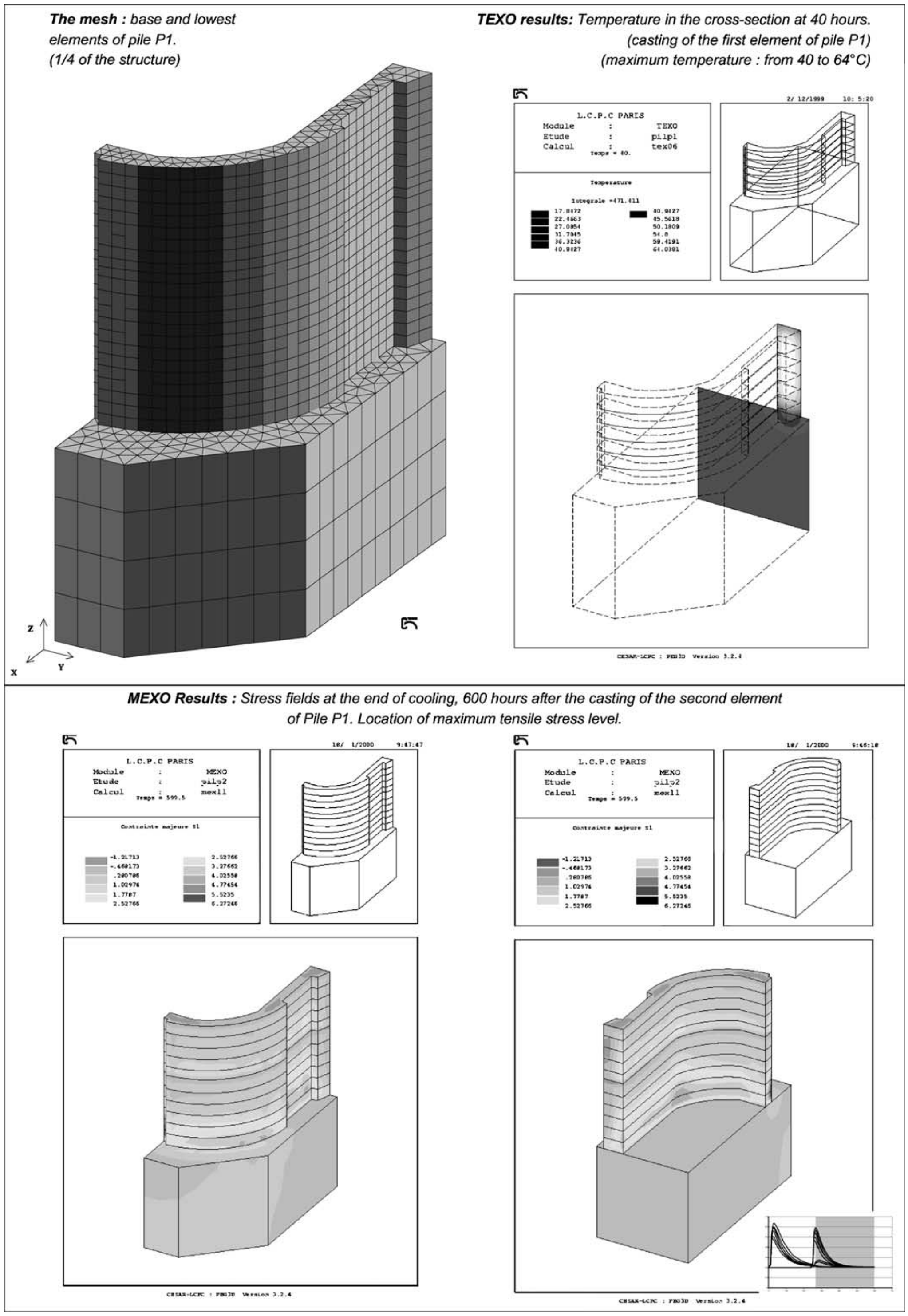


Fig. 11. Thermo-mechanical calculation: casting of pile P1—Viaduct of Verrières (CESAR-LCPC) [31].

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