# THERMAL FIELDS IN LARGE REINFORCED CONCRETE CONSTRUCTIONS DURING THE HYDRATION

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## Abstract

Hydration of a silicate binder is a highly exothermic reaction, thus it is possible to characterize the hydration process from the development of temperature of reactive mixtures. The calorimetric isoperibolic method is a very simple and relatively accurate method for the monitoring of hydration heat. The received experimental data are helpful for the formulation of a model of thermal behaviour of a large monolithic reinforced concrete structure.

**Key words**: Cement, hydration heat, chemical admixtures, calorimeters, reinforced concrete.

# 1. Hydration of cement

Hydration of cement is a exothermic reaction; the minerals contained in cement react with water and the products are badly soluble compounds, whose fixed connections form the microstructure of the hardening concrete. The intensity of the production of hydration heat depends on the rate of active reactions, conditioned by the mineralogical content of cement, by the presence of active admixtures and also on the environment.

The total amount of the produced hydration heat for a totally hydrated cement specimen is given as a sum of hydration heats corresponding to particular minerals, whose values differ substantially – see Table 1. This fact is able to explain the varying rate of hydration reactions, in the first rough estimate being proportional to the released hydration heat. Namely in the case of the pure Portland cement the dominating part of hydration heat belong to $C_3S$.

| mineral | hydration heat [$J.g^{-1}$] |
|---|---|
| $C_3A$ | 800-1280 |
| $C_3S$ | 380-540 |
| $C_4AF$ | 120-440 |
| $C_2S$ | 90-110 |
| CaO | 1116 |
| MgO | 812 |

Table 1: Values of hydration heat for some important minerals.

# 2. Methods for identification of hydration heat

In general, there are two basic types of methods for identification of hydration heat:

a) *the direct methods*, based on the recording of temperature changes of a test specimen under strictly defined boundary conditions,

b) *the indirect (dissolving) methods*, evaluating the hydration heat from the dissolving heat of the hydrated test specimens (after 7 and 28 days) in certain acid mixture.

The direct methods are rather accurate, but their output is only the total amount of hydration heat just at one selected time of the hydration progress. For the evaluation of hydration heat for a sample which is not hydrated completely, the test specimen has to be washed by the ethyl-alcohol and consequently desiccated.

The indirect methods enable us to record the evolution of quantities proportional to the intensity of production of hydration heat; the total amount of hydration heat can be then obtained from the integration of this intensity in time. Three mostly used types of indirect methods are:

i) *the adiabatic (or semi-adiabatic) methods* with no or negligible heat exchange between a test specimen and the environment during the whole measurement,

ii) *the isothermal methods* where a test specimen is tempered to a certain temperature and the thermal flux between a test specimen and the environment is recorded,

iii) *the isoperibolic methods* where the strictly prescribed conditions for the hydration are designed to simulate (as much as possible) the hydration process in a real building object.

Let us pay more attention to the method iii). This method can be applied both to the characterization of time-dependent production of hydration heat for binder mixtures and to the analysis of the modifying effect of chemical admixtures. Neglecting the thermal accumulation effect, we can consider the intensity of production of hydration heat as proportional to the measured temperature.

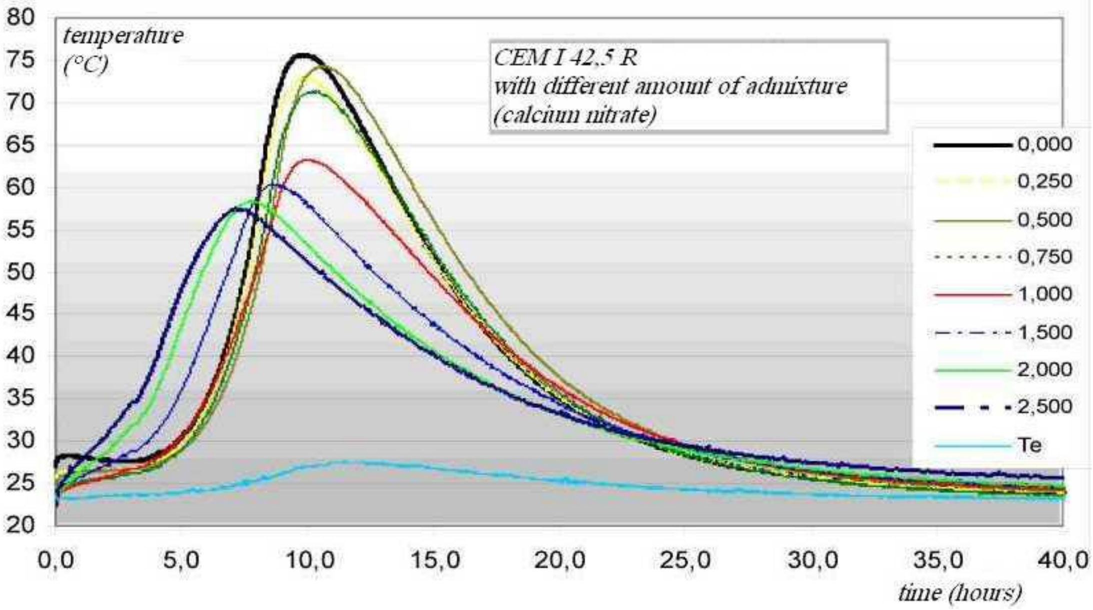

Figure 1: Evolution of hydration temperature in time.

Several colour curves at Figure 1 show the example of the time development of hydration temperature as a function of time. Various colours correspond to the different percentage of the calcium-nitrate-based admixture and (for comparison) to the environment.

# 3. Three-dimensional computational modelling

From the physical point of view, hydration is a complicated process, driven by a lot of interal thermodynamic relations and equilibrium conditions. The controlled evolution of temperature is needed especially in the case of massive monolithic constructions where a great mass of concrete is concentrated; such structure has a high thermal-accumulation ability and a relatively low amount of thermal losses through its surfaces. For the resulting development of the temperature the following influences seem to belong to the most relevant:

- the quality and amount of the applied cement,
- the geometrical configuration: the shape and the boundary conditions, determined by the foundation and boarding properties,
- the amount and concentrations of all chemical admixtures,
- the initial temperature of a concrete mixture and the time schedule of its depositing,
- climatic conditions.

Further influences, as the effect of cooling of the concrete surface, depend on the regime of the water treatment and with of the removal of boarding of particular fragments. However, the most important seems to be the first influence, whose direct connection with the reaction kinetic is evident; its evaluation, required by the computational modelling, can be performed using the calorimetric measurements.

The distribution of some temperature field *t* in an arbitrary volume, characterized by the Cartesian coordinates (*x*, *y*, *z*), and also in an arbitrary time $\tau$, can be obtained from one partial differential equation of evolution (of the parabolic type) in the form

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y \frac{\partial t}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z \frac{\partial t}{\partial z}\right)+\frac{\partial Q}{\partial \tau}-\rho.c\frac{\partial t}{\partial \tau}=0 \qquad (1)$$

where $Q$ is the energy of internal sources (in general a function of *x, y, z* and $\tau$), $\rho$ is the material density, *c* is the heat capacity and $\lambda$ is the thermal conductivity: in general it can be different in the directions *x, y, z*, which is distinguished by its index.

If (1) is formulated for certain domain $\Omega$ then its boundary $\Gamma$ can be divided into two non-overlapping parts, $\Gamma_1$ and $\Gamma_2$, where the mixed boundary conditions are prescribed. The non-homogeneous Dirichlet boundary condition with some prescribed function $\overline{t}$ is

$$t=\overline{t}\left(x,y,z,\tau\right) \text{ on } \Gamma_1 .$$

The remaining boundary condition

$$\lambda_x \frac{\partial t}{\partial x}\nu_x+\lambda_y \frac{\partial t}{\partial y}\nu_y+\lambda_z \frac{\partial t}{\partial z}\nu_z+q\left(x,y,z,\tau\right)+\alpha\left(x,y,z,\tau\right)\left(t-t_\infty\right)=0 \text{ on } \Gamma_2$$

is more complicated, containing the local outward unit normal vector ($\nu_x,\nu_y,\nu_z$), corresponding to particular points of $\Gamma_2$, the prescribed heat flux *q* and the a priori given thermal convection factor $\alpha$; $t_\infty$ refers to the temperature of the outer environment. Moreover the initial setting of *t* (for $\tau$ = 0) must be given. The numerical analysis of (1) with the above presented boundary and initial conditions can be seemingly done in the standard way, e.g. using the finite element technique and the Crank-Nicholson time-integration scheme by [3]; however, the reasonable setting of $q$, $Q$, etc. requires a lot of (not only) experimental work. The advantage of the original computational model, created at the Institute of Building Materials of the Faculty of Civil Engineering of the Brno University of Technology, is its ability to handle the changes of the domain geometry in time (respecting the fact that the concrete construction is created in several steps), the time-dependent internal generation of hydration heat, due to the age of each concrete element in the massive, and such surface phenomena, as the incorporation of the latent heat of evaporation, the influence of sun shining, the (nearly) periodic development of the climatic temperature in the day cycles, etc.

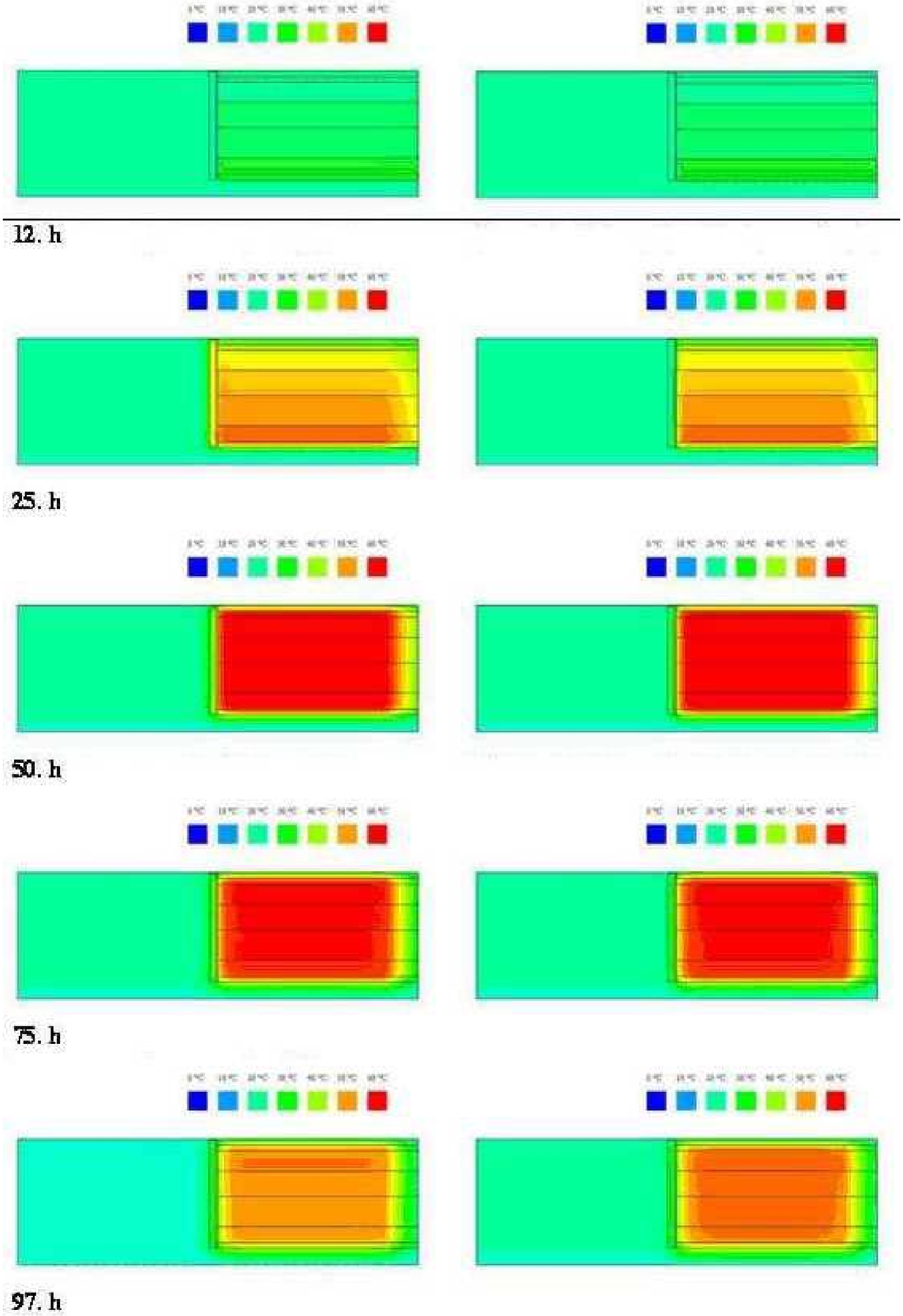

Figure 2: Distributions of temperature in the fragment with and without electrical heating

Figure 2 demonstrates a typical example of the development of temperature in time in one fragment of the large concrete construction, built in more steps – in each step one new fragment was added to the end of the existing one. The risk of undesirable stresses in the massive near the working interface the effect of additional electrical heating was tested and the corresponding changes in the temperature field were simulated during 97 hours. The left-hand pictures show the heating-modified temperature fields (for various times), the right-hand ones the same fields without such arrangement; especially at the last couple of pictures certain effect of additional heating is visible immediately.

# 4. Risk of cracking

The experimental measurements yield the hypothesis that the probability of crack initiation in concrete is proportional to the highest reached temperature. Since the hydration process has an exothermic character, the early age of concrete is a critical period, namely for the monolithic constructions. The temperature increase can endanger the final status of the whole structure from the point of view of its design properties, especially the inner concrete structure, the porosity, the often required water impermeability, etc. Even the final strength of concrete is usually correlated with the amount of the produced hydration heat.

The tensile stresses during the hydration heat generation in the early-age concrete are very small because of the negligible elasticity modulus. The risk of crack initiation increases with the stiffening of the concrete structure, accelerated in the first phase thanks to the hydration temperature. Therefore in the case of the waterproof concrete the maximum temperature is reduced using special arrangements, limiting the amount of binder and water for the mixture. The expected values of shrinking are shown at Figure 3, coming from [1].

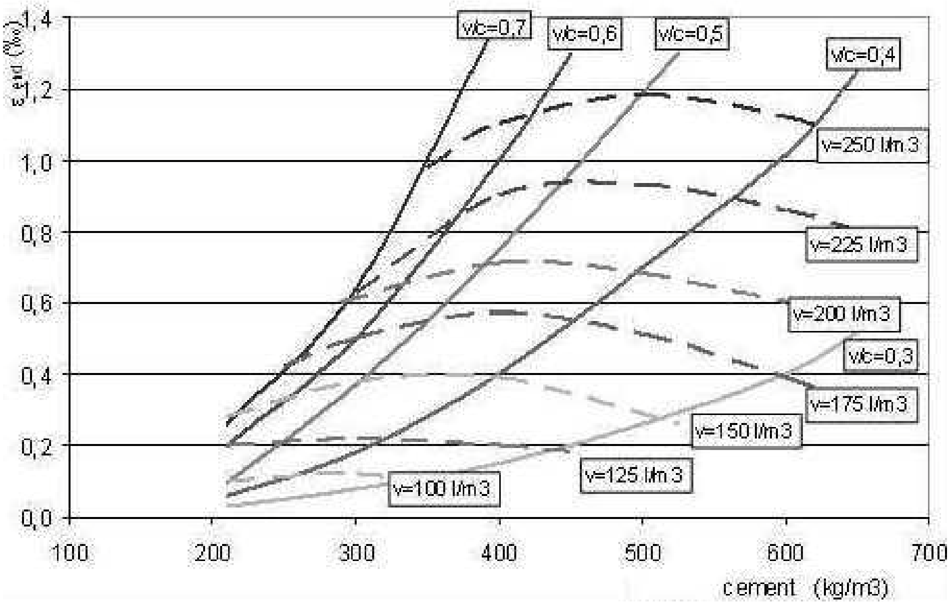

Figure 3: Concrete shrinkage as a function of the amount of cement and water.

# 4. Conclusion

The analysis of thermal fields in the early-age concrete, sketched in this paper, has been motivated by the practical action of the successive building of a large object. It makes use of some preliminary results, presented in [2], as well as of the experience with some special arrangements, including e.g. the additional reinforcements and the special boarding technology by [1].

However, the results are still far from being satisfactory. The further (both theoretical and experimental) research should come from the scale bridging between the microstructural information and the macroscopic description of material behaviour like (1), extended by some multiphysical considerations, namely by the thermo-mechanical ones with the proper analysis of the moisture influence (cf. [4] where much more references to the relevant literature, including physical principles, mathematical and numerical theory and commercial and research software, can be found, too) to predict the dangerous tensile stresses in the non-reinforced domains in the first step and to control the pre-stressing in the construction with respect of its future use in the second one.

**Acknowledgement.** This research is supported by the Ministry of Education, Youth and Sports of the Czech Republic, No. MSM 0021630511, DT7.

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