PREDICTION OF TEMPERATURE FIELDS OF MASSIVE CONCRETE STRUCTURES DURING HARDENING

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In this paper temperature fields of massive concrete structures during hardening are discussed. Temperature fields have been predicted using the ADINAT- program based on the finite element method. Calculation results and measurements made in practice are also presented. Reasons for differences between the calculated and measured results are discussed.

1. INTRODUCTION

It is important to know temperature fields when an attempt is made to predict volume changes, cracking risk, strength growth and possible strength loss caused by high temperature in massive concrete structures during hardening. Until now the prediction of a cracking risk in massive concrete structures has been based nearly always to temperature differences in cross section.

In order that temperature fields can be affected before casting, the different factors affecting the temperature fields must be known as well as the factors that can be changed or not. Furthermore, there must exist a method, by which the temperature fields during hardening can be predicted at least satisfactorily. This is important because most massive structures are large enough to be affected by hydration effects, but still small enough to be significantly influenced by ambient fluctuations.

In this paper the determination of temperature fields is made using the program ADINAT which is based on the finite element method. Principles of the additions to the program and the application of the program are discussed briefly. Moreover, results obtained from calculations and measurements made in practice are presented. Reasons for differences between calculated and measured results are also discussed.

2. FACTORS AFFECTING TEMPERATURES DURING HARDENING

The factors that affect temperature fields resulting from heat-of-hydration release are well known. The essential factors are:
- composition of concrete, mainly the type and quantity of cement
- initial temperature of concrete
- formwork and possible shuttering

- weather conditions
- dimensions of the structure.

In the planning phase of casting it is not possible to influence weather conditions and the size of the structure, but it is possible to influence the composition and initial temperature of concrete as well as shuttering, and this way to influence resulting temperatures during hardening.

In addition to the above-mentioned factors hardening temperatures can be affected by cooling the massive structures. The dimensions of most structures in practice are not, however, so large that use of the time-consuming and expensive cooling process should be made.

3. ON PREDICTION OF TEMPERATURES BY PROGRAM ADINAT

3.1 General

When it is desired to determine temperature fields during hardening, a differential equation for heat conduction containing inner heat source has to be solved. In two-dimensional case the equation is

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{q}{c\rho},$$

where λ, ρ and c are the thermal conductivity, the mass density and the specific heat of the material, T(x, y, t) is the temperature at a point with cordinates x, y at time t and q is the heat development in unit volume during the unit time.

Since the exact solution of heat conduction equation, when taking into consideration the initial and boundary conditions, is possible only in special cases, generally when cross section is regular, several methods suitable for manual calculation have been developed to solve the temperature fields in practice. These are usually based on the approximate solution of the heat equation in one-dimensional case.

Since numerical methods have become general along with computers, the use of difference and finite element methods for solving the heat equation has also become generalized.

3.2 Temperature fields calculated using ADINAT

ADINAT is a general program for solving stationary and nonstationary temperature fields and its application area is wide. The program is based on the finite element method. The theoretical basis of the program has been presented in literature /1, 2/.

It was not possible to use the above-mentioned program to solve temperature fields without additions because of the nature of internal heat generation.

Since in addition to time the quantity and rate of the internal heat generation are depend on temperature, which is unknown in the analysis, the solution has to be performed by iteration. Therefore, to the program ADINAT, a special heat loading program has been added, which by using element nodal point temperatures obtained in a previous iteration turn, determines the rates of the internal heat generation of the element for the new iteration turn in question. The rate of the internal heat generation is calculated for each element using the mean value of element nodal point temperatures at the beginning and end of time-step. For the first iteration turn the internal heat generation has been calculated by using the initial temperature of concrete.

Otherwise the program is suited without changes to the calculation of hardening temperatures. To the user the program offers the same advantages as the finite element method generally. In massive concrete structures division into finer mesh and finer time-step comes into question in cases where great temperature changes can be expected.

By means of the program it is also easy to take account of the effect of the joining structures and the ground on the temperature fields.

4. CALCULATIONS AND MEASUREMENTS RESULTS

4.1 Calculation basis

The internal heat generation of concrete is based on measurements made with a calorimeter. The expression of the internal heat generation of ordinary Finnish Portland cement concrete used in calculations is

$$Q = 8.4 + 379 \exp\left(-\frac{120}{N^{0.8}}\right), \qquad (\mathrm{kJ/kg})$$

where $N = \sum_{0}^{t} (T_c + 10)\Delta t$

t is time

T_c average concrete temperature during time-step.

The specific heat, thermal conductivity and mass density of concrete are assumed to be constant. The value of specific heat has been 1.05 kJ/kg · °C, thermal conductivity 7.9 kJ/m · h · °C and mass density 2400 kg/m^3.

When determining the overall heat flow from the structure directed outwards the effect of convection, formwork and insulation has been taken into consideration. The influence of radiation has been omitted.

The resulting heat transmission value α_R between the structure and environment has been calculated from the expression

$$\alpha_R = \left[\frac{1}{\alpha_k} + \left(\frac{\delta}{\lambda}\right)_f + \left(\frac{\delta}{\lambda}\right)_i\right]^{-1},$$

where α_k is the heat transfer coefficient of convection
δ the thickness of formwork and insulation
λ the thermal conductivity

The heat fransfer coefficient in the case of forced convection caused by wind has been calculated from the expression

$$\alpha_k = 20 + 14 \cdot v, \quad kJ/m^2 \cdot h \cdot {}^{o}C, \text{ when } v \leq 5 \text{ m/s}$$

$$= 25.6 \cdot v^{0.78}, \quad \text{"} \quad , \text{ when } v > 5 \text{ m/s}$$

4.2 Calculation and measurement results

Fig. 1 shows the time-temperature curves for a 1.2 m thick bridge slab, which was measured in practice at two points and calculated theoretically. The upper surface is covered with a tarpaulin and the lower side with a board form. In calculations, actual measured temperatures were used as outdoor temperatures. In determining heat transfer coefficients the speed of wind is estimated to be 2.0 m/s on an average. The calculation is carried out for one-dimensional case.

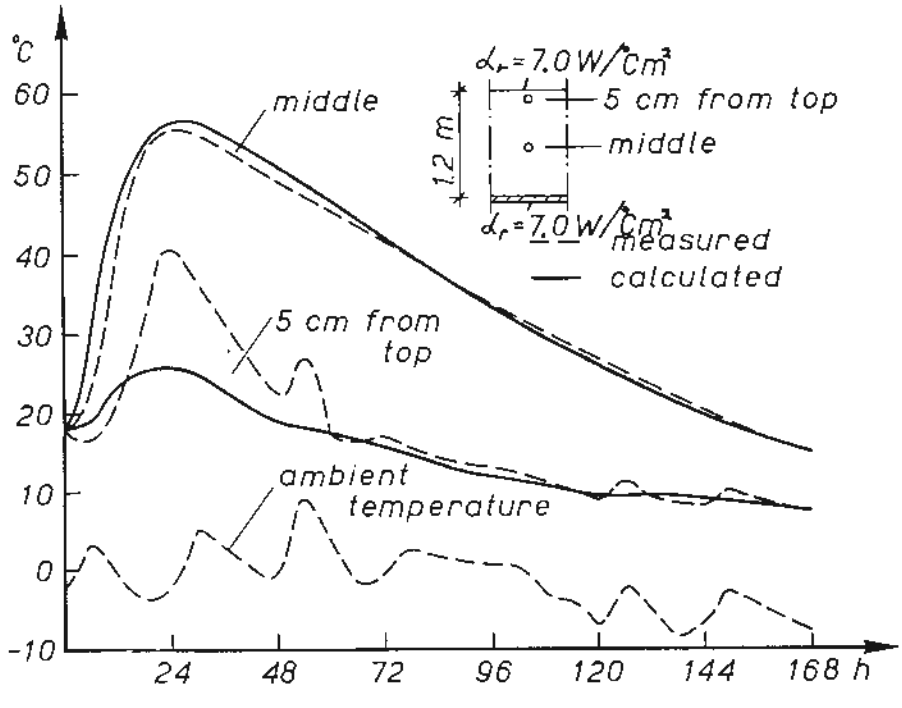

Fig. 1. Time-temperature curves measured and calculated for the 1.2 m thick bridge slab.

Fig. 2 gives the rates of heat generation per unit volume obtained theoretically for elements being situated in the middle and at the upper surface. A considerable difference in the rate of heat generation in its initial phase results from temperature differences between the inner part and the outer surface.

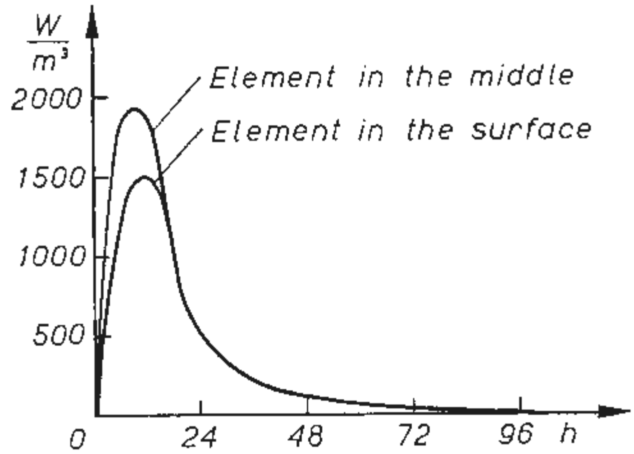

Fig. 2 The theoretical rates of heat generation per unit volume for elements being in the middle and upper surface.

Fig. 3 shows the time-temperature curves for a 1.2 m thick foundation, which have been measured at two points and calculated theoretically. The upper surface is covered with a tarpaulin. In determining the heat transfer coefficient the speed of wind was estimated to be 2.0 m/s as above.

The calculation is carried out one-dimensional and the effect of the ground is considered by extending the element mesh 2.5 m into the ground under the base. The specific heat of the ground, thermal conductivity and density were taken as constants. The specific heat value of the ground was 1.15 kJ/kg • °C, the value of thermal conductivity was 3.1 kJ/m • h • °C and that of density 1800 kg/m^3. The initial temperature of the ground on the surface is assumed to be the temperature outdoors and at the depth of 2.5 m constant. Between before-mentioned points the change is assumed to be a 3-degree curve.

By means of the program it is theoretically possible to examine the effect of different factors on temperature fields of massive structures during hardening. Examples are shown in Figs. 4 and 5.

In Fig. 4 the results from calculations are shown, in which the effect of outdoor temperature on the mid-point temperatures of the cross section are examined. All other factors that affect temperatures are kept constant in the calculations carried out.

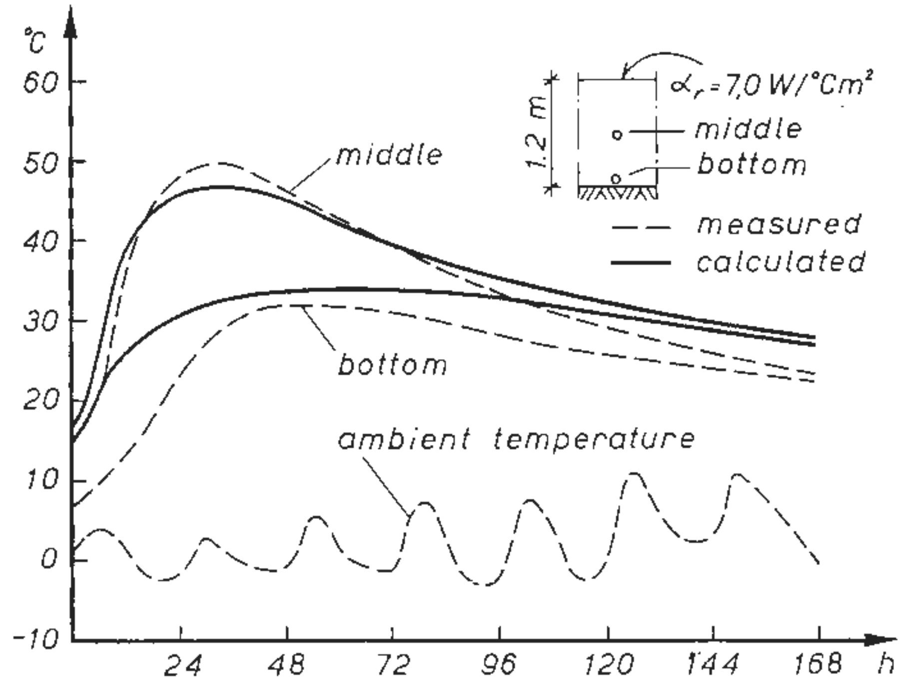

Fig. 3 Time-temperature curves measured and calculated for the 1.2 m thick base of foundation.

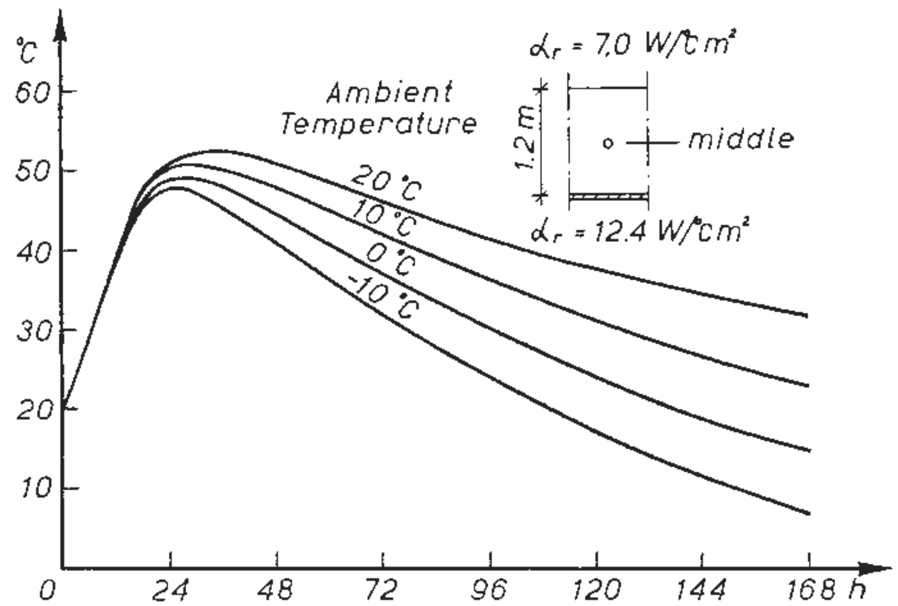

Fig. 4 Effect of outdoor temperature on the mid-point temperatures of the cross section.

Fig. 5 shows the effect of two-dimensional heat flow on the temperatures at the points between the corner and mid-point of a concrete block, 2 x 2 m^2 in size. The calculation is carried out as two-dimensional taking the symmetry into account.

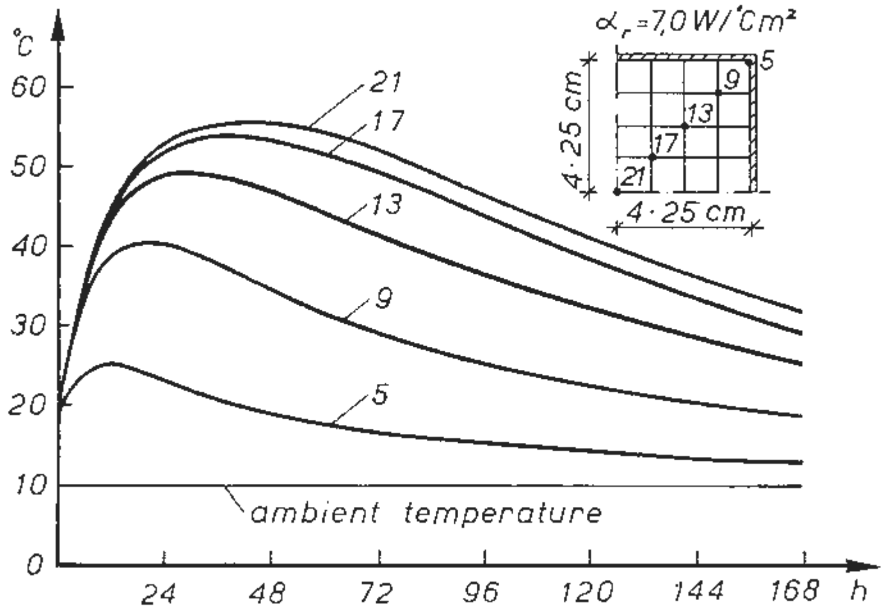

Fig. 5. The effect of two-dimensional heat flow on the temperatures at the points between the corner and mid-point of a concrete block.

4.3 Examination of results

As Figs. 1 and 3 indicate the measured and calculated results from the inner parts of the structures agree very well with each other. On the other hand in the case of the slab surface and in the case of the foundation base at the bottom the differences are already considerable.

Differences between the measured and calculated results in the surfaces of the structure primarily result from inaccuracy in the estimation of insulation and wind effect as well as the exclusion of radiation effect. Furthermore, the upper surface was not covered all the time.

The main reason for differences between the results in the lower side of the base are the differences in the temperatures of the fresh concrete, the differences in ground temperatures and the inaccuracies in the thermal properties of the ground.

5. CONCLUSIONS

The finite element method as an calculation method is very practicable in the determination of temperature fields of massive concrete structures during hardening.

The temperature fields can be usually predicted with a satisfactory accuracy. The prediction of the temperature fields in the inner parts of the structure is much more accurate than that of the outer parts. The worse the protection, the greater the differences in the outer parts.

If temperature fields are predicted in advance by means of calculations, differences in real temperatures can be expected due to the following reasons:

- the initial temperatures differ from each other
- the outdoor temperature is unknown; the average temperature values at the time of casting must be used
- the estimation of form and insulation effect is inaccurate
- the effect of wind has to be estimated
- the radiation effect remains generally without consideration
- the heat generation model of concrete does not exactly correspond to reality
- inaccuracies in the thermal properties of concrete and related structures.

Literature

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