MATURITY DEVELOPMENT IN YOUNG CONCRETE
Temperature Sensitivity, Strength and Heat Development

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ABSTRACT

In the planning of the production of concrete structures it is important to know the properties of the young concrete. Young means the time period from the concrete is mixed up to some week of age. In order to determine formwork stripping times, to estimate the need for protection against early freezing and to calculate the risk for thermal cracks, it is necessary to describe the behaviour of the young concrete. Tests have been done on normal and high strength concrete to examine mechanical and thermal properties of young concrete. Temperature sensitivity and compressive strength development have been obtained by compressive strength tests on concrete cubes cured in water at four different temperature levels. The heat of hydration development in the concretes have been obtained from adiabatic and semi-adiabatic tests. These tests, together with the strength development tests at different temperature levels, have been optimized to be fulfilled within a week for a certain mixture.

Key words: maturity function, temperature sensitivity, heat development, strength growth

1 INTRODUCTION

The behaviour of the mature concrete depends on the young concrete behaviour, see Byfors (1980), Pitkänen (1984), Young (1986), Emborg (1989), Kjellsen (1990), van Breugel (1991), Ekerfors, Jonasson and Emborg (1993), Jonasson (1994a), Westman (1995), Hedlund (1996) and Westman(1999). The most important area, where knowledge in the maturity and temperature development of the young concrete is essential, is the hardening control of young concrete, which amongst others includes determination of formwork stripping times, estimation of need for protection against early freezing, assessments of measures to be taken at winter concreting and calculation of deformations and stresses due to variations in the temperature and moisture field. This latter area is most essential in situations where high tensile stresses may cause cracking that decreases the durability protection in severe environmental conditions. The character of the young concrete can be described by different properties of physical or chemical nature. In these contexts, the physical properties have been taken into consideration from both mechanical and thermal approach, respectively.

A basic property is the heat of hydration, which is important to know in planning of the production of concrete structures. The heat of hydration also plays a dominant role in some cases - like at winter concreting and when casting massive structures. To determine the heat development, the concrete can be tested by calorimetric methods, see for example Jonasson (1994a). From such temperature measurements and known testing conditions, the heat development can be determined, which gives a basis for studies of temperature and maturity development in concrete structures at general conditions, see among others Ekerfors (1993), Jonasson (1994b), Jonasson, Groth and Hedlund (1994) and Ekerfors (1995).

The strength development and temperature sensitivity are properties of great importance regarding for instance formwork stripping times. The increase of strength has a strong relation to the heat development, which, among other things, is depending on the chemical nature of the cement. The compressive strength development can be the basis for the estimation of other properties as tensile strength and Young's modulus. The compressive strength is very simple to measure. Here, it has been done by compression tests of 100 mm cubes cured in water at different temperature levels. The evaluation of such tests gives the temperature sensitivity of the mixture. The temperature sensitivity can be described as the strength development dependency on temperature in relation to a chosen reference temperature, and may also be named maturity function.

In this paper, the following new features and improvements of already existing methods for description of thermal and mechanical properties, are given:

- A new simplified and rational procedure for determination of the compressive strength development and the temperature sensitivity function is described. Special interest has been devoted to the times of testing for obtaining the compressive strength development in order to optimize the procedure to get relevant measurements with a minimum of concrete volume. The prerequisite requirement is that all test specimens of one concrete have to be taken out of one mixture. Thus, possible variations between different mixtures can be avoided.

- A new evaluation method to obtain temperature sensitivity is presented. The maturity function, see Eq. 2, is determined by calculation of rate relations for the compressive strength development. Measured values of compressive strength will be fitted to congruent linear equations in logarithmic time scale.

- The compressive strength development is evaluated in a different way than the temperature sensitivity. The compressive strength development at exactly 20°C is described partly by an exponential function fitted to measured values of compressive strength from the simplified procedure, and partly by an adjustment to a measured 28-days strength value, when this is known, see Eqs. 10-18.

- The fluctuation of the temperature in the tempered water baths has been taken into consideration. Hereby, small temperature variations are allowed, which simplifies the regulation techniques.
- Adiabatic and semi-adiabatic measurements are made in parallel tests. In this way, the different tests may be used as a mutual control on each other, which leads to a relatively great reliability in obtained results.

2 COMPRESSIVE STRENGTH DEVELOPMENT AND TEMPERATURE SENSITIVITY

2.1 Measurement of Compressive Strength and Temperature According to the Quick Procedure

100 mm concrete cubes are cured in water at four different temperature levels, here 5°C, 20°C, 35° and 50°C, respectively. For each curing temperature, the concrete temperature is measured continuously in the centre of two cubes. The simplified procedure means that 1) the compressive strength is measured on concrete cubes taken from the same concrete mixture and 2) the times of testing are optimized to get relevant measurements with a minimum of concrete volume. All compressive strength measurements are planned to take place at daytime within one working week (=five calendar days). The compressive strength is measured at three or four times for each curing temperature. Each compressive strength value is a mean value of three cubes. Here, the total minimum amount of cubes is forty-five. Therefore, a small volume of concrete, in this case 50 l, is possible to use for all compressive strength tests of one concrete mixture.

2.2 Evaluation of Temperature Sensitivity

The evaluation of temperature sensitivity, see for instance Byfors (1980), is based on the measured compressive strength development for each temperature series.

The temperature sensitivity for a concrete is determined by iterative calculations of rate relations for the compressive strength development at different temperatures. The maturity function, β_T in Eq. 2, is used to estimate the equivalent time of maturity, t_e, which is related to a reference temperature of 20°C and expressed by

$$t_e = \int_0^t \beta_T \cdot dt \quad \text{(h)} \qquad (1)$$

where

$$\beta_T = \begin{cases} \exp[\theta \cdot (1/293 - 1/(T+273))] & \text{when} \quad T > -10°\text{C} \\ 0 & \text{when} \quad T \leq -10°\text{C} \end{cases} \qquad (2)$$

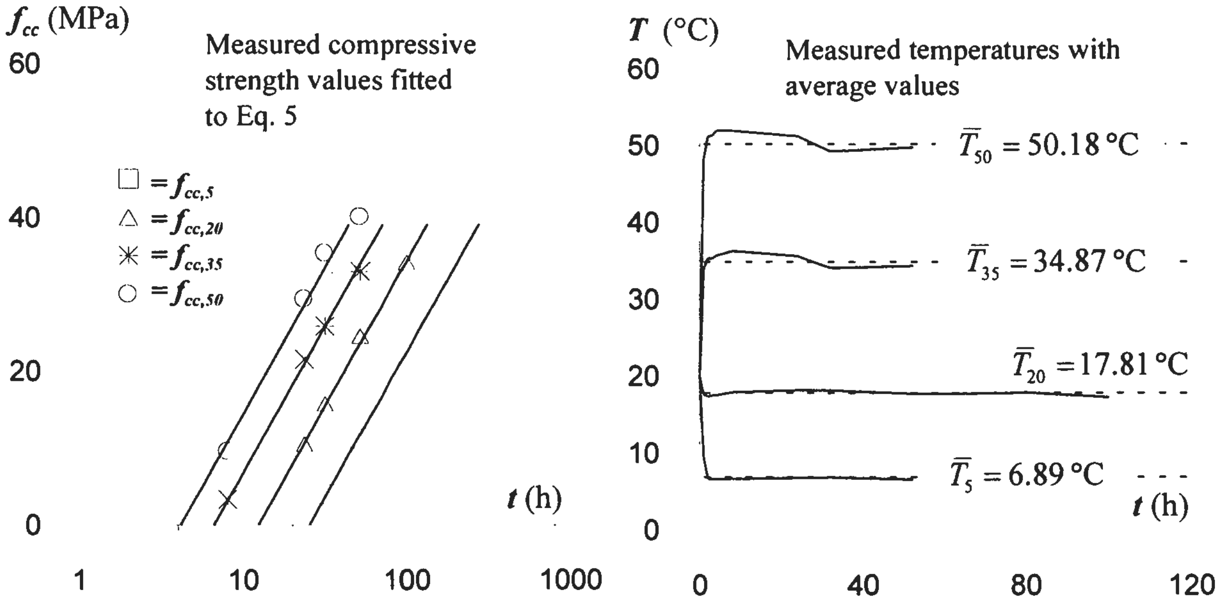

Figure 1 Examples of measured compressive strength values and temperatures.

and

$$\theta = \theta_{\text{ref}} \cdot \left(\frac{30}{T+10}\right)^{\kappa_3} \quad \text{(K)} \tag{3}$$

where T = concrete temperature (°C);

θ_{ref} = reference value for the specific activation energy (K); and

κ_3 = constant; θ_{ref} and κ_3 are fitting parameters.

The so called 20°C-bath has a mean temperature not so far from 20°C, typically about 18°C. So, as a starting procedure, the equivalent time, t_e, for the 20°C-bath is calculated as

$$t_{\text{e}} = \beta_{20} \cdot t_{20} \quad \text{(h)} \tag{4}$$

where t_{20} = time at the compressive strength development for the 20°C-bath (h) and

β_{20} = maturity factor for the 20°C-bath for the actual mean temperature; a first approximation of Eqs. 2 and 3 with θ_{ref} = 5000 K and κ_3 = 0.5. Note that typically $\beta_{20} \approx 0.9$ is valid.

The compressive strength values are fitted by the least square method to linear equations by

$$f_{\text{cc},T} = k_{20} \cdot \ln(t_T) + m_T \quad \text{(Pa)} \tag{5}$$

where $f_{\text{cc},T}$ = compressive strength development at an average temperature from a water bath of temperature T (°C) (Pa)

k_{20} = coefficient fitted to the strength development from the 20°C-bath, same value for all water baths (Pa/h)

t_T = time at an average temperature in a water bath (h)

m_T = constant, varies for the different water baths (Pa)

Based on Eq. 4, the maturity function is also described as

$$\beta_T = \frac{t_e}{t_T} \tag{6}$$

With Eqs. 2 and 3 and with values of β_T according to Eq. 6 for each temperature bath evaluated by the use of t_T from Eq. 5 the parameters θ_{ref} and κ_3 are established. The iteration cntinues until the maturity function is stable.

Now, the average temperature is calculated for each water bath. The fluctuation of the average temperature for every water bath has been taken into consideration by calculations of temperature equivalent times associated with the current average temperature by

$$t_{\bar{T}} = \sum_i \Delta t_{\bar{T}_i} \quad \text{(h)} \tag{7}$$

$$\Delta t_{\bar{T}_i} = \frac{\beta_{T_i}}{\beta_{\bar{T}}} \cdot \Delta t_{T_i} \quad \text{(h)} \tag{8}$$

where $t_{\bar{T}}$ = temperature equivalent time associated with a constant temperature $\bar{T}$; i = index of a time step; T_i = measured average temperature (°C) during time step Δt_{T_i}, and $\bar{T}$ = average temperature (°C) for the studied water bath denoted with T (°C).

A value of β_{20} (the β-factor of the average temperature of the measured 20°C-series) can now be settled by Eqs. 2 and 3 with the difference that all times are adjusted in accordance with the average temperature. By iterative calculations of Eqs. 4-6, 2, 3, 7 and 8 with all t_T exchanged to $t_{\bar{T}}$, the values of $\beta_{\bar{T}}$ at each average temperature are found and the maturity function is established. This procedure is chosen to eliminate the effects of small temperature fluctuations in the hardening temperatures during the testing period.

2.3 Compressive Strength Development at Exactly 20°C

When the maturity function is known, the time at all measured compressive strength values are recalculated to the time of maturity by

$$t_e = \beta_{\bar{T}}\, t_{\bar{T}} \quad \text{(h)} \tag{9}$$

All measured compressive strength values for one concrete is now a function of time of maturity, t_e. These values can now be fitted to Eq. 11, which gives a basis of analysis of the compressive strength development in the young concrete. When the 28-days strength value is measured later, the compressive strength development curve is adjusted to give the correct value at 28 days time of maturity by:

I) Eq. 11 is chosen to be valid up to $f_{cc}/f_{\infty} = 0.75$.

II) At the interval from $f_{cc} = 0.75 \cdot f_{\infty}$ to $f_{cc} = f_{28}$ an addition to Eq. 11 is made by use of a polynomial function so f_{28} is reached at exactly $t_e = 672$ h, see Eqs. 13-17. The polynomial has been chosen with the condition that the derivative will be continuous at $f_{cc} = 0.75 \cdot f_{\infty}$. Several polynomial functions have been tested and Eq. 15 gave a satisfactory result.

III) When $t_e > 672$ h $f_{cc} = f_{28}$ is used.

In accordance with I) - III) above, the compressive strength development curve is described in four time sequences by Eqs. 10-18:

1) $0 < t_e \le t_0$: $f_{cc} = 0$ (Pa) (10)

2) $t_0 < t_e \le t_\Delta$: $f_{cc} = f_{\infty} \cdot \left[1 - \exp\left(-\left((t_e - t_0)/t_2\right)^q\right)\right]$ (Pa) (11)

where

$$t_\Delta = t_e(0.75 f_{\infty}) = t_0 + t_2 \cdot \exp\left[\left(\ln(-\ln 0.25)\right)/q\right] \quad \text{(h)} \tag{12}$$

3) $t_\Delta < t_e < 672\,\text{h}$: $f_{cc} = f^*_{cc}(t_e) + \Delta f_{28} \cdot \eta$ (Pa) (13)

where

$$\Delta f_{28} = f_{28} - f_{\infty} \cdot \left[1 - \exp\left(-\left((672 - t_0)/t_2\right)^q\right)\right] \quad \text{(Pa)} \tag{14}$$

$$\eta = 2\xi^2 - \xi^3 \qquad \text{for} \quad 0 \le \eta \le 1 \tag{15}$$

$$\xi = \left(\frac{\ln(t_e) - \ln(t_\Delta)}{\ln(672) - \ln(t_\Delta)}\right) \qquad \text{for} \quad 0 \le \xi \le 1 \tag{16}$$

and

$$f^*_{cc}(t_e) = f_{\infty} \cdot \left[1 - \exp\left(-\left((t_e - t_0)/t_2\right)^q\right)\right] \quad \text{(Pa)} \tag{17}$$

4) $672\,\text{h} \le t_e < t_{\infty}$: $f_{cc} = f_{28}$ (Pa) (18)

where f_{cc} = compressive strength (Pa); f_{28} = compressive strength at 28 days equivalent time of maturity (Pa); f_{∞} (Pa), t_0 (h), t_2 (h) and q are curve fitting parameters.

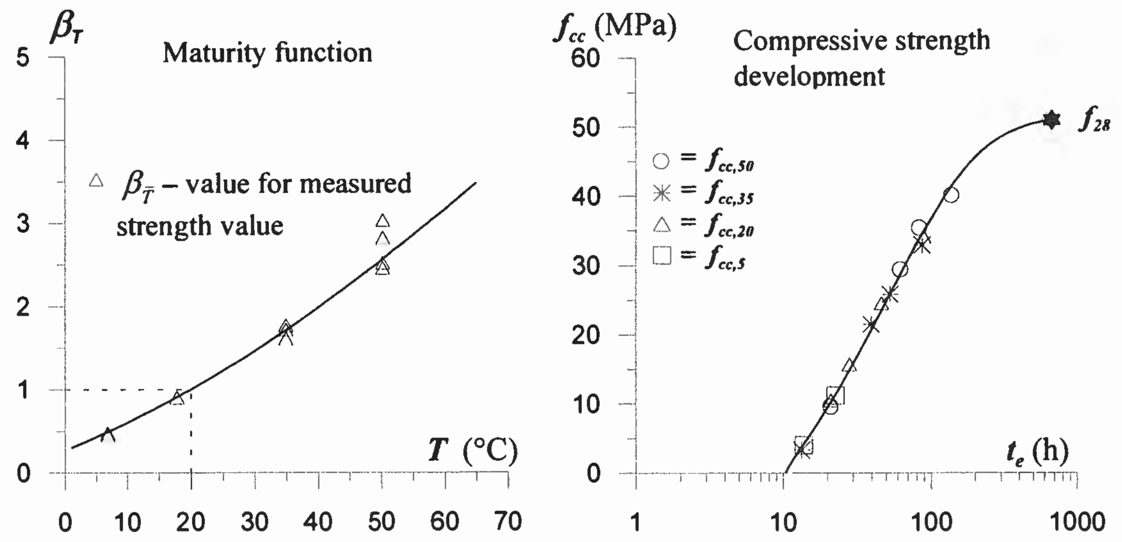

Figure 2 Example of the resulting maturity function according to Eqs. 2 and 3 and the compressive strength development curve calculated by Eqs. 10-18.

3 HEAT OF HYDRATION

3.1 General

Calorimetric methods are suitable to obtain the heat of hydration. Here, two types of calorimetric methods have been used: Adiabatic and semi-adiabatic methods. For adiabatic and semi-adiabatic tests the temperature has continuously been recorded in the hardening concrete specimens. Based on recorded temperatures the heat development has been calculated by calorimetric methods, which are based on the heat-conduction equation, see Özizik (1980). By using two typically different testing methods a possibility for control is achieved and this procedure increases the reliability of obtained results. Calculated heat development should coincide for adiabatic and semi-adiabatic tests.

Cylindrical shaped concrete specimens (about 5 l) have been cured under adiabatic and semi-adiabatic conditions, respectively, during five days. The temperature course in the specimens has been recorded.

3.2 Adiabatic Tests

Adiabatic tests have been performed by regulation of the surrounding air temperature of a concrete specimen in such a way that no heat exchange has occurred between the test specimen and the environment. The adiabatic situation for the concrete specimen has continuously been simulated by the regulation technique. This regulation requires great accuracy in order to obtain reliable results. Calculations of the adiabatic heat development are very easy to perform. The heat is obtained by

$$W = \rho \cdot c \cdot \int_{T_S}^{T} dT \quad \text{(J/m}^3\text{)} \tag{19}$$

where ρ = density of concrete (2350 kg/m³); c = specific heat (1000 J/(kg K)); T = measured temperature (°C) and T_S = start temperature of an adiabatic hardening process (°C).

The values of ρ and c are chosen as constants to simplify the evaluation procedure. This requires that the *same* values of these parameters must be used when the heat is calculated at applications.

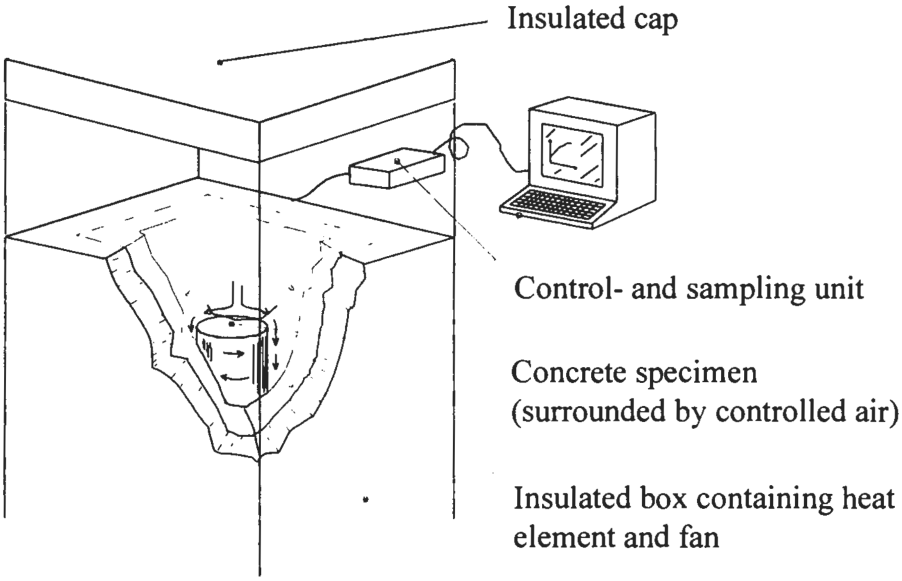

Figure 3 Adiabatic testing equipment. A fresh concrete specimen is placed in a room of air in a well insulated box. The box contains a heat element and a fan. Regulation of the air temperature is made by the control and sampling unit.

3.3 Semi-adiabatic Tests

Semi-adiabatic tests have been performed by registration of the temperature in a concrete specimen that is insulated with cellular plastic. Contrary to the adiabatic tests the temperature development is here measured for actual conditions. In other words, the temperature is measured without regulation of the conditions of insulation. The semi-adiabatic situation is representative for a certain concrete structure, which increases the quality of this type of testing.

The heat under semi-adiabatic conditions is obtained by

$$W = W_T + W_E \quad \text{(J/m}^3\text{)} \tag{20}$$

where

$$W_T = \rho \cdot c \cdot \int_{T_S}^{T} dT, \quad W_E = \rho \cdot c \cdot a \cdot \int_{0}^{t} (T - T_E)dt$$

a = cooling ratio (1/s); t = time (s), and T_E = environmental temperature (°C)

Evaluations of the semi-adiabatic heat development require consideration of current heat losses during the testing period. The heat losses are calculated by the cooling ratio, a, that has been determined by analysis of a separate cooling test for mature concrete.

The semi-adiabatic tests are made in two parallel tests. The resulting heat of hydration from the tests is chosen to be presented as a function of equivalent time of maturity, t_e, in Eq. 1, in the following way

$$W = W_{\text{cem}} \cdot B \quad (\text{J/m}^3) \tag{21}$$

with

$$W_{\text{cem}} = W_U \cdot \alpha^* \quad (\text{J/kg}) \tag{22}$$

and

$$\alpha^* = \exp\left[-\lambda_1 \cdot \left(\ln\left(1 + t_e/t_1\right)\right)^{-\kappa_1}\right] \tag{23}$$

where W = heat of hydration per volume of concrete (J/m^3); W_{cem} = heat of hydration per weight of binder (J/kg); W_U = heat of hydration per weight of binder for $\alpha^* = 1$ (J/kg); B = binder content of the concrete (kg/m^3); α^* = (fictitious) level of reaction; λ_1, t_1 (h) and κ_1 are fitting parameters associated with the value of W_U (J/kg).

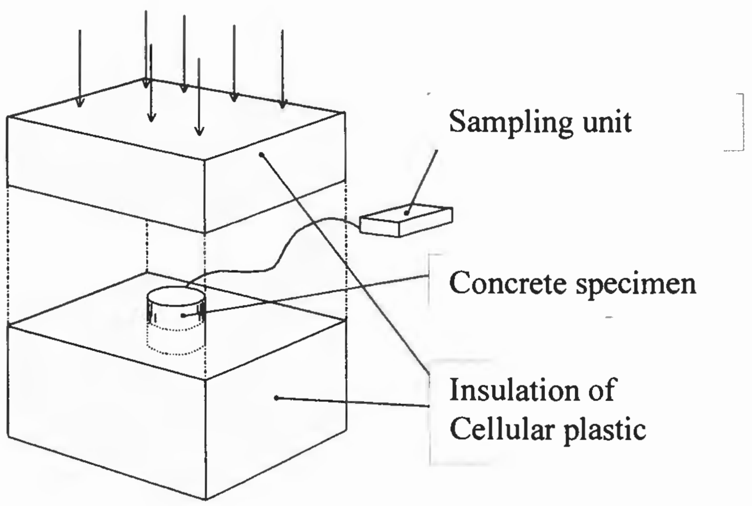

Figure 4 Semi-adiabatic equipment. A concrete specimen is placed in a block of cellular plastic. The temperature is measured in the hardening concrete specimen.

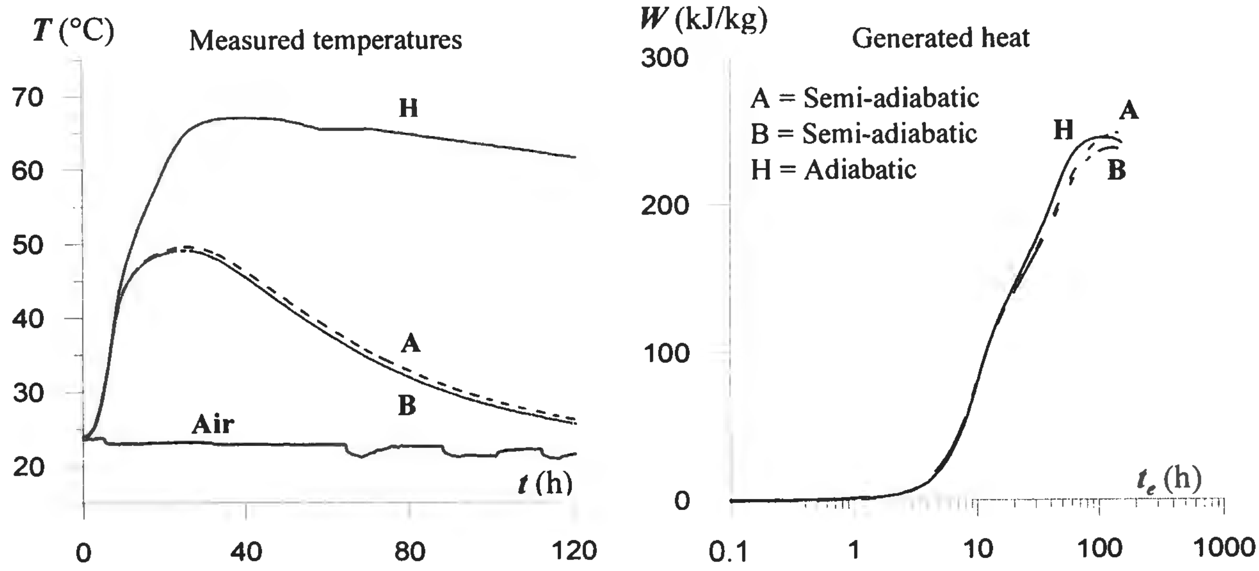

Figure 5 Measured temperatures from adiabatic and semi-adiabatic tests, generated heat of concrete by Eqs. 19-20.

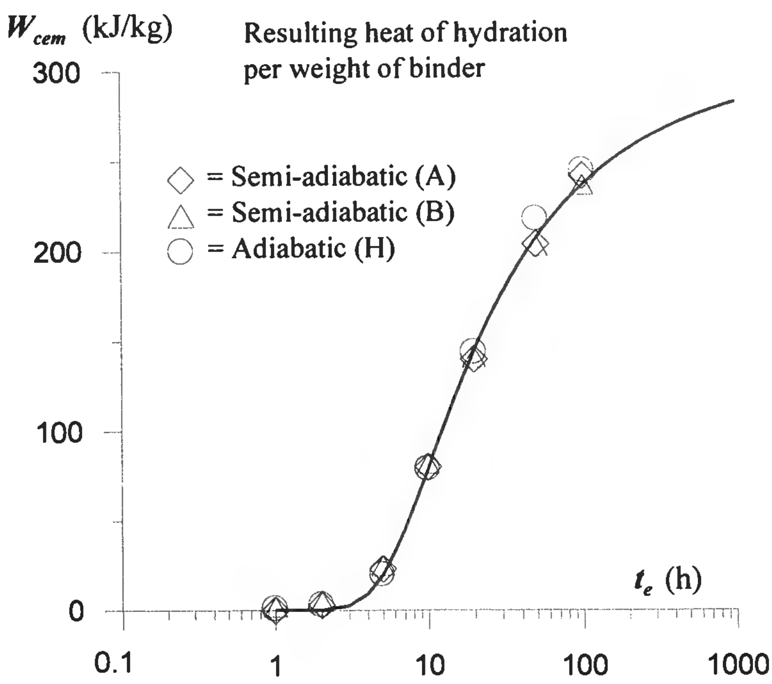

Figure 6 Generated heat by Eqs. 21-23.

4 SUMMARY

By measuring compressive strength development at different temperatures, rate relations have been calculated. This gives, after an iterative procedure, a description of the temperature sensitivity, which usually is called the maturity function. The compressive strength developments result in a function of time at exactly 20°C. These relationships form a basis to calculate the strength development at variable temperature conditions.

The presented simplified procedure is a rational process to obtain the temperature sensitivity and the strength development. Only one mixture of about 50 l per mixture is used, and all tests are done within a working week. Because of the simple test equipment, the short time to do the tests and the evaluations, it is also a cost-effective method.

For adiabatic and semi-adiabatic tests the temperature has continuously been recorded in the hardening concrete specimens. Based on recorded temperatures and known temperature sensitivity the heat development has been evaluated by calorimetric methods. By using two different test methods, adiabatic and semi-adiabatic conditions, a possibility for control is achieved. The reliability of obtained results increases, as resulting heat development at the reference temperature should coincide for the adiabatic and semi-adiabatic evaluations.

The adiabatic tests have been performed by regulation of the surrounding air temperature of a concrete specimen in such a way that no heat exchange has occurred between the test specimen and the environment. This regulation requires great accuracy in order to obtain reliable results.

Semi-adiabatic tests have been performed by registration of the temperature in a concrete specimen that is insulated with cellular plastic. Contrary to the adiabatic tests the temperature is here measured for actual conditions without any regulation. The semi-adiabatic situation is representative for a certain concrete structure, which increases the quality of this type of testing. Evaluation of the semi-adiabatic heat development requires consideration of current heat losses during the test period. The heat losses are calculated by a cooling ratio that has been determined by analysis of a separate cooling test for mature concrete.

Both the adiabatic and the semi-adiabatic tests can be performed within a working week in conformity with the tests of strength developments at different temperature levels mentioned earlier. This means that for a certain concrete mixture all necessary tests and the requested strength development, the temperature sensitivity and the heat development can easily be evaluated within a working week. Hereby, all necessary tools exist for the tested concrete mixture to calculate temperature and strength developments at different structural applications.

REFERENCES

van Breugel K. (1991) *Simulation of hydration and formation of structure in hardening cement-based materials,* Technical University of Delft, Faculty of Civil Engineering, Dissertation, Delft 1991.

Byfors J. (1980) *Plain concrete at early ages*, Swedish Cement and Concrete Research Institute, CBI Forskning/Research Fo 3:80, Stockholm.

Ekerfors K. (1993) *Maturity development in concrete at early ages*, in proceedings of the Nordic concrete research meeting in Göteborg 1993, pp 44-46.

Ekerfors K. (1995) *Maturity Development in Young Concrete. Temperature Sensitivity, Strength and Heat Development*, Division of Structural Engineering, Luleå University of Technology, Licentiate Thesis 1995:34L, 136 pp.

Ekerfors K., Jonasson J.-E. and Emborg M. (1993) *Behaviour of young high strength concrete* in proceedings of the International Symposium on *High Strength Concrete* June 20-24, Lillehammer, pp 691-697.

Emborg M. (1989) *Thermal Stresses in Concrete at Early Ages*, Luleå University of Technology, Division of Structural Engineering, Doctoral Thesis 1989:73D, Luleå.

Hedlund H. (1996) *Stresses in High Peformance Concrete due to Temperature and Moisture Variations at Early Ages*, Luleå University of Technology, Division of Structural Engineering, Licentiate Thesis 1996:38L, Luleå.

Jonasson J.-E. (1994a) *Modelling of temperature, Moisture and stresses in Young Concrete*, Luleå University of Technology, Division of Structural Engineering, Doctoral Thesis 1994:153D, Luleå.

Jonasson J.-E. (1994b) *Betongens värmeutveckling*, avsnitt 16.2 i Betonghandboken - material, utgåva 2, Svensk Byggtjänst, Stockholm.

Jonasson J.-E., Groth P. and Hedlund H. (1994) *Modelling of temperature and moisture field in concrete to study early age movements as a basis for stress analysis*, in proceedings of the International RILEM Symposium on *Thermal cracking in concrete at early ages*, October 10-12, 1994 in Munich, pp 45-52.

Kjellsen K.O. (1990) *Physical and Mathematical Modelling of Hydration and Hardening of Portland Cement Concrete as a Function of Time and Curing Temperature*, Institutt for bygningsmateriallære, Norges tekniske høgskole, doktor ingeniøravhandling 1990:76, Trondheim.

Pitkänen P. (1984) *Prediction of temperature fields of massive concrete structures during hardening.* Nordic concrete research, Publ: No. 3, pp 183-190.

Westman G. (1995) *Thermal Cracking in High Performance Concrete - Viscoelastic models and laboratory tests*, Luleå University of Technology, Division of Structural Engineering, Licentiate Thesis 1995:27 L, Luleå.

Westman G. (1999) *Concrete Creep and Thermal Stresses -. New Creep Models and their Effects on Stress Development*, Luleå University of Technology, Division of Structural Engineering, Doctoral Thesis 1999:10 L, Luleå.

Young J.F. /editor/ (1986) *Properties of concrete at early ages.* American Concrete Institute, Special Publication SP-95, Detroit 1986.

Özizik M.N. (1980) *Heat Conduction*, JohnWiley & Sons, New York.