Control of heat curing based on the prediction of concrete strength

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ABSTRACT

The production capacity of precast concrete plants can be improved by controlled heat curing. Existing systems measure maturity or degree-hours providing information about the strength development, but not sufficient data for online control of heating.

A heat control system has been developed based on an on-line predictive calculation of the temperature behavior of concrete and a maturity-strength model. It provides an accurate estimation on when the prestress release or demoulding strength will be reached, and, if needed, heats concrete till the prediction shows that the target strength can be obtained. The system is in use in several precast factories in Europe.

Key words: maturity, strength prediction, heating control, precast production,

1. INTRODUCTION

Heat curing in precast production is needed for high production capacity. Till now the used curing times have been rough estimates and generally excessively long for securing the required strength at demoulding. However, accurate control of heating of concrete in precast production is desired, because it saves heating costs and the concrete strength at demoulding or prestress release can be maintained uniform. The uniform strength at prestress release will also reduce camber variations caused by the prestressing forces.

In the production process, the concrete temperature varies due to variations in aggregate, cement and mixing water contents and on their temperature at the time of mixing. Also, the ambient temperature in the production hall is changing. The release of hydration heat is strongly dependent on the temperature of concrete and the degree of hydration. Measurement systems have been introduced for monitoring maturity of concrete. This information can be used for evaluation whether the required strength has been reached or not. A normal maturity system does not, however, predict accurately the heat and strength development, and can not be used for accurate heat control.

A system has been developed for on-line control of heating of concrete in precast production. This system measures the concrete temperature, calculates maturity and strength, and controls the heating of the moulds based on a target strength and desired time point of mould removal or detensioning of prestress. It also saves the measured data for later studies and quality control documentation.

2. ACCURATE CONTROL OF HEATING REQUIRES PREDICTION

2.1 Control principle

If the temperature of concrete has been increased by heating, the cement reaction will also be accelerated and will increase the concrete temperature further. The decision of the correct time for stopping the heating must be based on a prediction that estimates that the concrete will reach the target strength at the desired time point without further heating. This prediction requires a comprehensive model for the future process.

2.2 Prediction models

For accurate prediction of the temperature and strength development, several models are required:

- Loss of heat from concrete to the ambient air
- Influence of heating
- Influence of temperature on reaction rate (basis for maturity model)
- Liberation of hydration energy as a function of maturity (heat generation model)
- Development of strength as a function of maturity

A schematic presentation of the heat flows is presented in Fig. 1.

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Figure 1- Definitions of heat flows for temperature prediction

Heat transfer models
The models used for heat loss q_L and influence of heating q_H, are simple:

$$\begin{aligned} q_L &= k_L\left(T_C - T_S\right) \\ q_H &= k_H\left(T_H - T_C\right) \end{aligned} \qquad (1)$$

In the formula T_C stands for the temperature of concrete, T_S for the temperature of surrounding air and T_H for the heating water temperature. The values of the heat loss coefficient k_L and the heating coefficient k_H are determined by fitting the measured values from full-scale tests to the model.

Reaction rate models
The Arrhenius model proposed by Freiesleben Hansen and Pedersen *[1]* is used to model the influence of temperature on reaction rate. It defines maturity M as an equivalent age at 20 degrees Celsius:

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(2)

In the model R is the universal gas constant and T_c is the temperature of concrete at the measuring point. The activation energy E_A determined by Freiesleben Hansen and Pedersen was 33.5 kJ/mol, and it has since been proved to be applicable for rapid hardening cements in several test series by comparing the heat generation curves of concrete samples that have different starting temperatures *[2]*. This method is more accurate than using strength measurement of concrete for determination of the activation energy, because it considers the chemical reaction and the corresponding liberation of hydration heat.

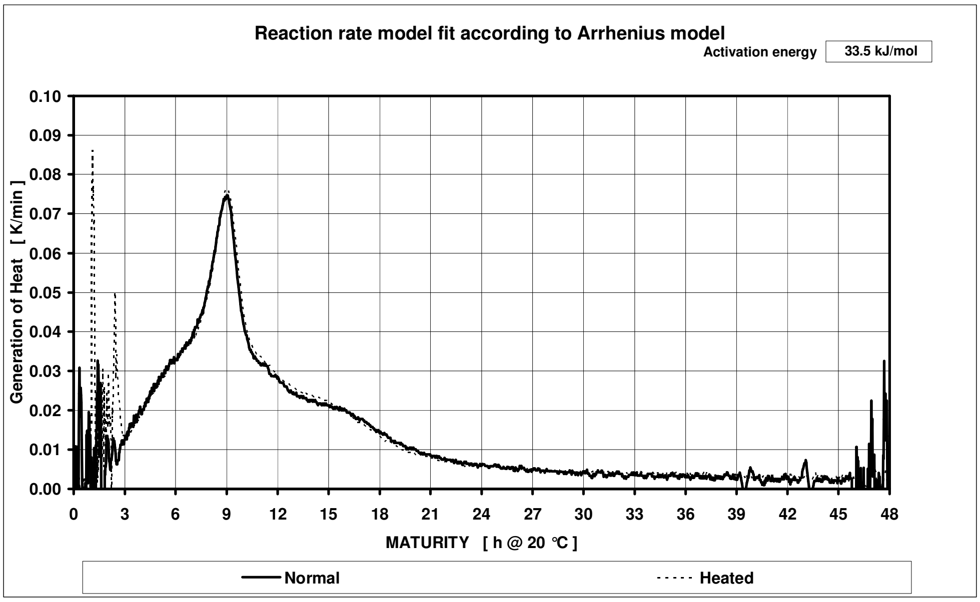

Figure 2- Adaptation of Arrhenius model parameters

In Fig. 2 an example of the verification of the activation energy is presented. The curves show the liberation of hydration heat of concrete samples with starting temperature of 24 degrees Celsius and same concrete preheated by microwave heating to 37 degrees Celsius. The maturity corrected curves coincide well, when 33.5 kJ/kmol is used in the maturity model.

Determination of the model for hydration energy flow, q_H is based on a function of maturity and temperature:

$$q_H = f(M, T_C) \tag{3}$$

The heat liberation curve has been measured with the semiadiabatic test, where the concrete sample is placed in an insulated container *[3,4]*. The temperature of the sample and ambient air are measured with constant intervals. The reaction heat for each interval is calculated based on the heat increase and the estimated heat loss from the container. For modelling the heat generation a combination of two asymmetric double sigmoidal pulses has been used. A single pulse has the following mathematical model:

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$$q_H = A\left[\frac{1}{1+e^{-\left(\frac{M-M_S+\frac{W_1}{2}}{W_2}\right)}}\right]\left[\frac{1}{1+e^{-\left(\frac{M-M_S+\frac{W_1}{2}}{W_3}\right)}}\right] \tag{4}$$

Both asymmetric pulse models have five parameters for adjusting the area (***A***), peak position (***M_S***), width (***W_1***) and start and end slopes (***W_2, W_3***). The curves have been fitted based on a least squares error calculation.

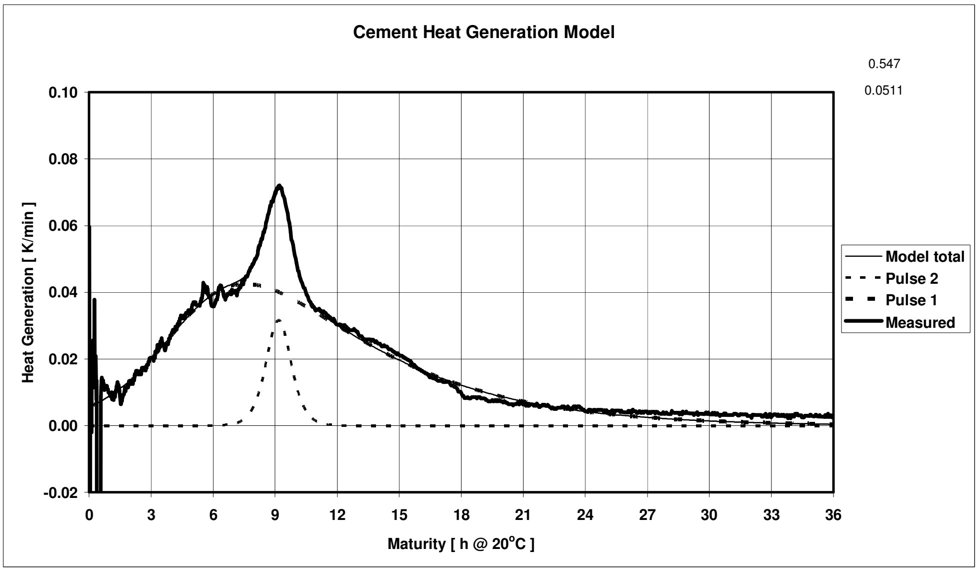


Figure 3- Heat generation results and fitted model

In Fig. 3 an example of fitting two asymmetric pulses to measured data is shown.

The temperature effect on liberation of hydration heat ***q_{HT}*** at real temperature ***T_C*** is the same as the maturity model presented earlier.

$$q_{HT} = q_H \, e^{\frac{E_A}{R}\left[\frac{1}{293} - \frac{1}{T_C + 273}\right]} \tag{5}$$

Strength model

The early strength of hydrating concrete shows usually S-shaped curve. A logistic model is suitable and gives a good fit for the early strength development.

$$S = S_2 - S_2 \left[\frac{1}{1 + \left(\frac{M}{M_P} \right)^{a}} \right] \tag{6}$$

The least square fit has also been used for finding the model parameters ***S_2***, ***M_P*** and a.

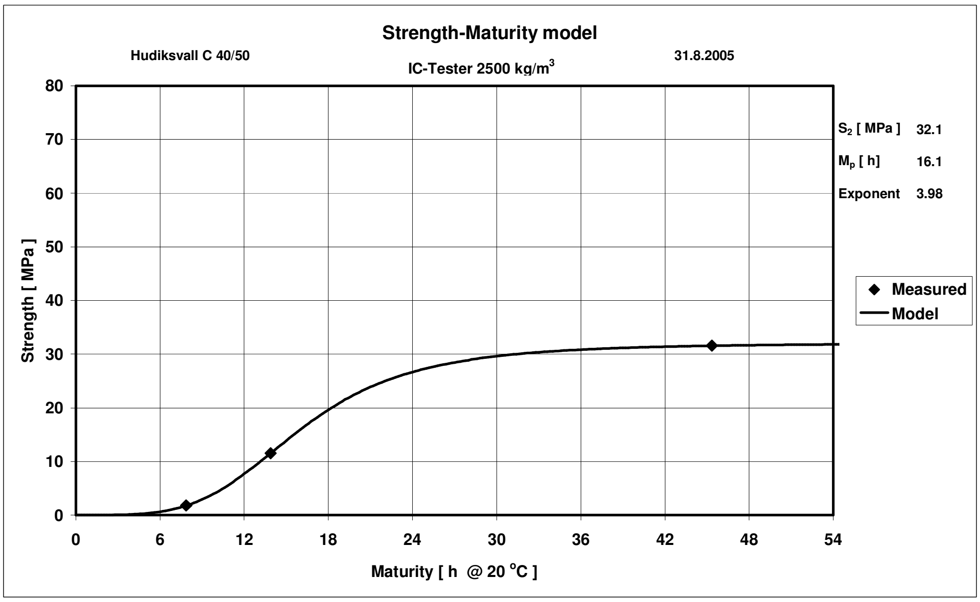


Figure 4- Compressive strength results and model curve

In Fig. 4 the measured values are fitted to Eq. (6).

Before testing hollow-core concrete samples were compacted to constant density, stored in an insulated container used for semiadiabatic tests, and tested for compressive strength at about 6, 8, and 24 hours after mixing.

3. THE SYSTEM IN OPERATION

A temperature sensor for concrete is installed in the mould. The measurement and calculation of maturity starts when the concrete is poured into the mould. The measurement is updated once per minute, and after the maturity has been calculated, the program performs an incremental prediction of the subsequent temperature development assuming that no heating is used. For each increment, the heat loss to the ambient air, the liberated heat and the strength are calculated with the models described above. The incrementation continues till the strength required at demoulding or release of prestress has been reached. Then the program compares the required time to the available time defined by production planning. If the predicted time exceeds the available time, the heating will stay on. A schematic diagram of the system is shown in Fig. 5.

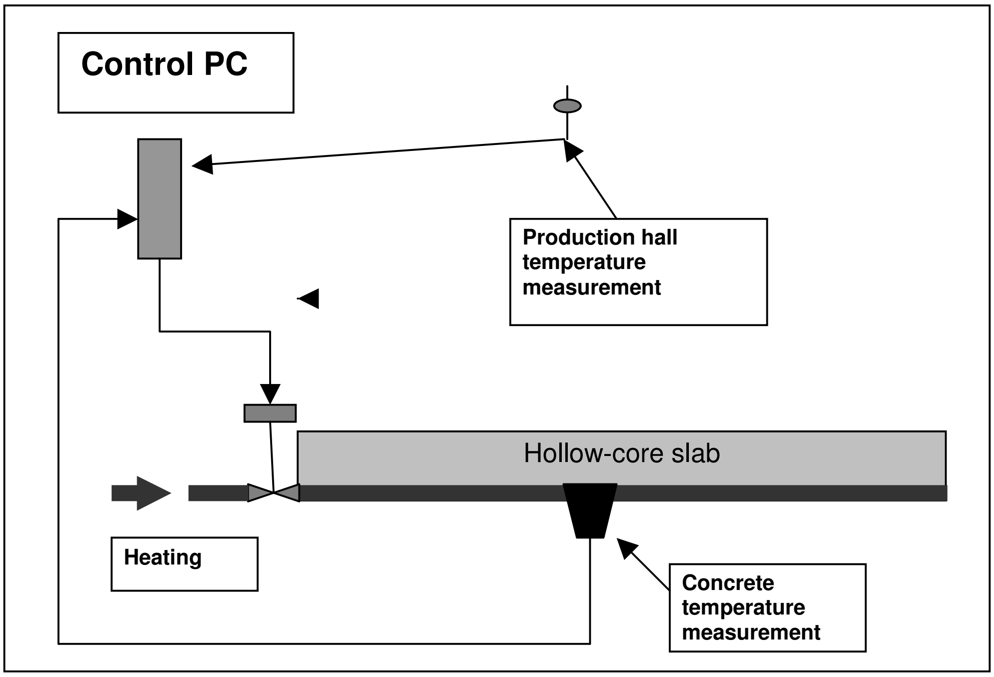
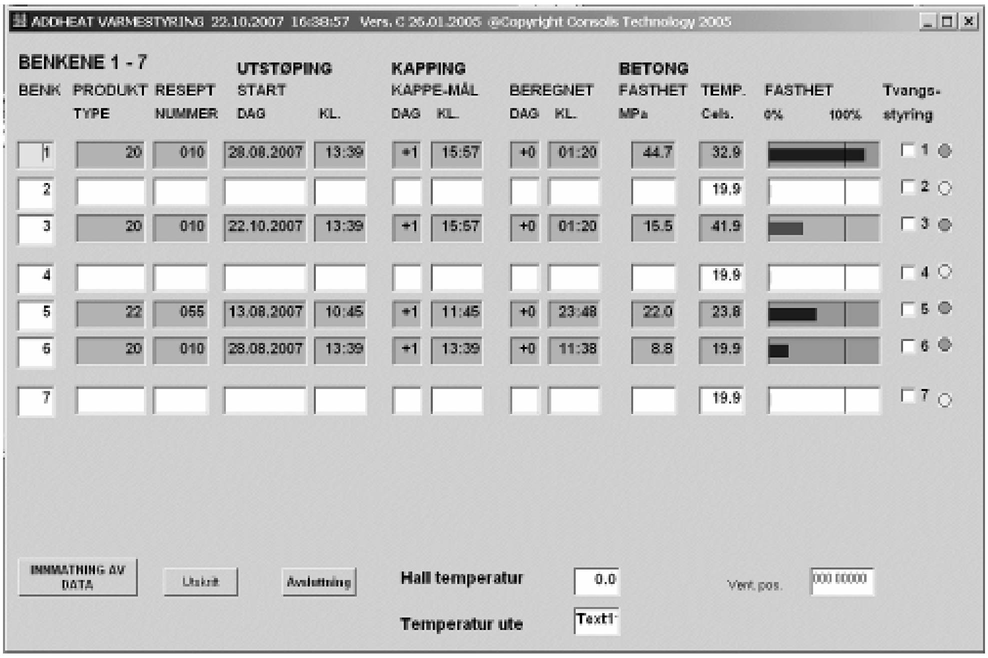


Figure 5- Heating control system

During operation of this system, the operator needs to select the product and concrete mixture proportions and fill in the times for concrete pouring and the desired time of mould removal. After this, the program will automatically display the predicted mould removal time and control the heating valves. The program also checks if the available time is sufficient when heating is used. If not, a warning signal will be displayed. Fig. 6 shows the main display of the control program.



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BENKENE 1 - 7

BENK	PRODUKT TYPE	RESEPT NUMMER	UTSTØPING START DAG	KL.	KAPPING KAPPE-MÅL DAG	KL.	BEREGNET DAG	KL.	BETONG FASTHET MPa	TEMP. Cels.	FASTHET 0% 100%	Tvangs-styring
1	20	010	28.08.2007	13:39	+1	15:57	+0	01:20	44.7	32.9		☐ 1 ●
2										19.9		☐ 2 ○
3	20	010	22.10.2007	13:39	+1	15:57	+0	01:20	15.5	41.9		☐ 3 ●
4										19.9		☐ 4 ○
5	22	055	13.08.2007	10:45	+1	11:45	+0	23:48	22.0	23.8		☐ 5 ●
6	20	010	28.08.2007	13:39	+1	13:39	+0	11:38	8.8	19.9		☐ 6 ●
7										19.9		☐ 7 ○

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Figure 6- Display of control system in use in Norway.

4. RESULTS IN FULL SCALE PRODUCTION

4.1 Prediction performance

Fig. 7 shows an example of the action of the control system in a precast factory. In the beginning of the curing process, the heating stays on till the concrete temperature has reached about 30 degrees Celsius. After the dormant period, at 5 hours after casting, the reaction heats the concrete, and the concrete temperature starts to rise. At about 8 hours the intensity of the reaction reaches its maximum. The target strength 26 MPa is reached little before the desired point of time, 14 hours 10 minutes after casting.

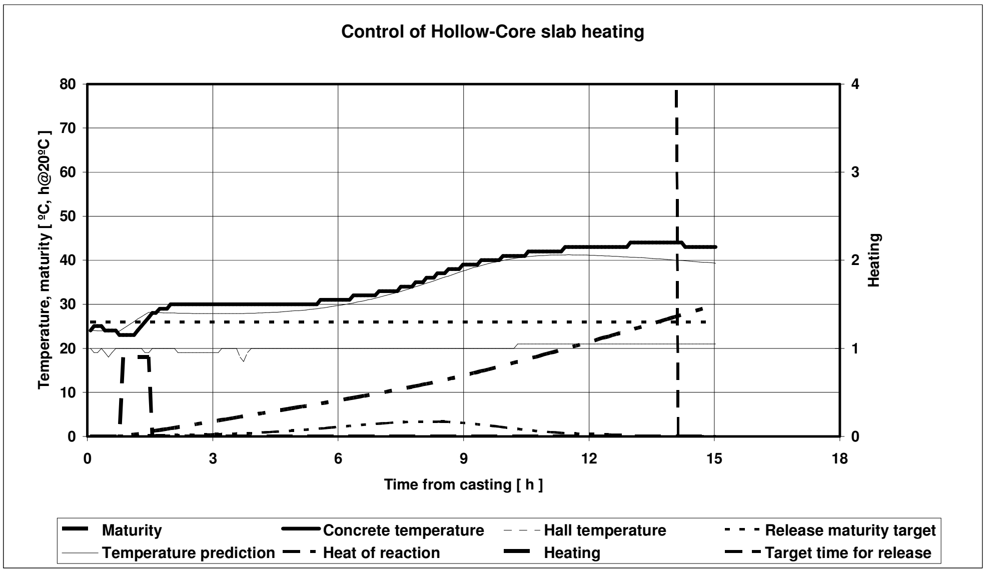

Figure 7- Measured and predicted temperature and maturity

4.2 Control performance

In a factory producing prestressed hollow-core slabs, 49 beds were produced during a three month period using the same concrete mixture. The beds were cast during the morning and afternoon shifts and released early next morning. Before installation of the control system all beds were heated. After the control system was installed, only the beds cast late in the afternoon were heated. This meant that the heating had been unnecessary for about 80 % of all beds. The time heating was on varied between 0.5 to 4 hours, as the available curing times in the beds varied between 10 to 20 hours. When the system controlled the heating, the time when the target strength was reached was in most cases less than 30 minutes from the desired time in all observed cases. Two cases with too early hardening were probably a result of manual extra heating. Fig. 8 shows the heating times and errors between the desired time and the real time when the target strength was obtained.

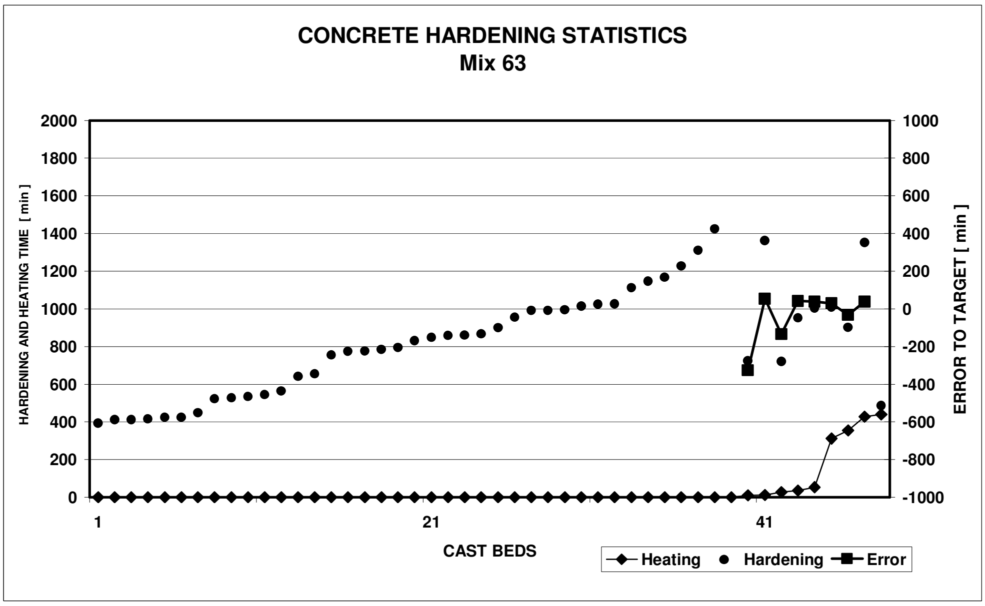

Figure 8- Accuracy of heating control system

5. CONCLUSIONS

An accurate system for control of heating in precast plants has been designed using continuous temperature measurement and advanced models for prediction of heat losses, liberation of hydration energy and strength-maturity relationships. The system is able to control the heating in the beginning of the curing period so that the target strength is reached at the desired time. The system has been applied successfully in precast production of prestressed hollow-core slabs and railroad sleepers when high and controlled early strength has been essential.

Future applications of the system will include the use of wireless sensors for easy installation, support and monitoring of the system applications over corportate wide computer network and integration of the heat curing system to the batching and mixing control systems at the precast plants. The heating control system will also be integrated to the production planning system.

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