Computer Interactive Maturity System (CIMS).

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A curing technology system has been developed that makes it possible to plan and optimize concrete construction in advance based on laboratory testing of the concrete.

The system operates on a personal computer and allows temperature monitoring of 12 channels simultaneously with simulation calculations on the computer.

Keywords: computer simulation, control, curing, heat development, maturity, temperature monitoring.

1. Introduction

Specifications normally refer to minimum concrete age or strength to be obtained before exposure of the concrete to stresses is permitted to ensure durable concrete structures. This may be in relation to moist curing or heat curing procedures, protection against early freezing, hot or cold weather construction etc. If these can be converted into specifications to minimum maturity of concrete it is directly applicable in concrete construction, and quality control and assurance has been made operational.

The concept behind CIMS is that if you have tested your concrete property development in the laboratory at a constant temperature, and if you simulate or measure the concrete temperature development in the structure, you are able to predict accurately the concrete strength at any given time anywhere in the structure to control that construction complies with the assumptions made in the planning.

All you have to do is test your concrete heat and strength development in the lab and identify the possible range of parameters regarding

- form type
- degree of insulation
- stripping time
- casting temperature

These may then be combined and the construction simulated until the optimum process for your job has been found.

The 4 parameters listed above are normally the only free control parameters granted the contractor. Other control parameters that may be modified to a certain extent within specifications are

- concrete type
- cement type
- cement content

whereas the 2 final parameters - structural dimensions and weather - normally are outside the contractor's influence!

2. The elements of CIMS /1/.

A. Maturity function

The rate of hardening is to very large extent determined by the temperature of the concrete.

If the temperature of the concrete is raised the hardening is accelerated.

This is handled mathematically with the maturity function. Maturity is defined as equivalent age at 20°C.

$$M_{20} = \int_0^t H(\Theta) \cdot dt$$

where $H(\Theta)$ is the so-called temperature function, i. e. the relative rate of hardening at temperature Θ compared to the rate at 20°C.

$$H(\Theta) = \exp\left[\frac{E}{R}\left(\frac{1}{293} - \frac{1}{273 + \Theta}\right)\right]$$

An expression of $H(\Theta)$ for Portland cements has been found to fit
This has the form of the well-known Arrhenius expression for chemical reactions.

B. Concrete heat development

During the hardening of the concrete, heat is developed. The most appropriate method to determine the heat development properties of a concrete is adiabatic calorimetry. This way the temperature increase in a concrete test specimen hardening without heat exchange with the surroundings is measured. Once the composition and heat capacity of the concrete in question are known, the measured temperature increase can be converted into specific heat development: kJ per kg cement. With good approximation a mathematical representation of this can be shown through 3 parameters: Q_∞, τ_e and α:

$$Q(M) = Q_\infty \cdot \exp\left[-\left(\frac{\tau_e}{M}\right)^\alpha\right]$$

C. Concrete strength development

The maturity development forms part of the mathematical evaluation of the hardening process. Therefore this value is immediately accessible. In case specifications for the strength of the concrete at the stripping time are made, this specification can be converted into an equivalent maturity requirement based on a measured strength development connected with trial castings. (Alternatively the property development of the concrete including the strength development may form part of the calculation routines.) Analogous to the heat development this can - with a good approximation - be described through the parameters σ_∞, τ_e and α through the expression:

$$\sigma(M) = \sigma_\infty \cdot \exp\left[-\left(\frac{\tau_e}{M}\right)^\alpha\right]$$

D. Heat exchange with the environment

In practice, concrete in structures will never be cured adiabatically but will exchange heat with the environment. This will normally result in a heat loss from the hardening concrete. A useful parameter for estimation of heat loss is the coefficient of heat transmittance.

The Coefficient of Transmittance = *cot*

The coefficient of transmittance is a measure of the degree of insulation applied. In the following, only *cot* for convective heat transmission is included.

The value of the *cot* is determined by the mould applied, the insulation used, and the convective cot_k between system and surroundings. The *cot* can be determined by calculation by

$$cot = (1/cot_k + (e/\lambda)_{insul} + (e/\lambda)_{mould})^{-1} \quad kJ/m^2 \cdot h \cdot {}^oC$$
$$= (m_k + m_{insul} + m_{mould})^{-1} \quad kJ/m^2 \cdot h \cdot {}^oC$$

The convective *cot* for enforced convection can be approximately calculated as a function of the wind velocity v :

$$cot_k = 20 + 14 \cdot v \quad (kJ/m^2 \cdot h \cdot {}^oC) \quad \text{for } v \leq 5 \text{ m/s}$$
$$cot_k = 25.6 \cdot v^{0.78} \quad (kJ/m^2 \cdot h \cdot {}^oC) \quad \text{for } v > 5 \text{ m/s}$$

E. Temperature stress in hardening concrete

With the existing knowledge of today it is impossible to state exact limits to the temperature differences which are acceptable in hardening cross sections. According to experience it is wise to attempt to stay within the following limits for temperature stress:

For cooling of cross section after stripping: max . difference 20^{o}C over the cross section.

For construction joints and structures with greatly varying cross section dimensions: max. difference 10-20^{o}C.

In the latter case, greater differences in temperature may be acceptable under certain conditions, since relaxation effects in the hardening concrete may reduce the stress.

F. Duration of moist curing

One purpose of the curing of concrete is to make sure that the concrete is not exposed to stresses that promote cracks resulting from temperature differences, and another is to prevent drying and to make sure that the reaction between cement and water will take place through the whole of the concrete cross section and provide the hardening intended with the mix proportion of the concrete.

Under the assumption of proportionality between the heat development and the degree of reaction, the degree of reaction can be expressed through the parameters resulting from the measured adiabatic heat development for the concrete:

$$r = \frac{Q}{Q_\infty} = \exp\left[-\left(\frac{\tau_e}{M}\right)^\alpha\right]$$

if this expression is logged, we have

$$M = \tau_e/(-\ln r)^{1/\alpha}$$

Then the criterion for the curing can be put into words thus: a suitable part of the theoretically achievable degree of reaction, e.g. no less than 90% must be achieved, i.e. $r = 0.9$.

G. Frost resistance

In case a hardening concrete freezes before a certain minimum degree of hardening has been achieved, the concrete may be damaged permanently. Therefore it is necessary to make criteria for when the hardening concrete is frost proof.

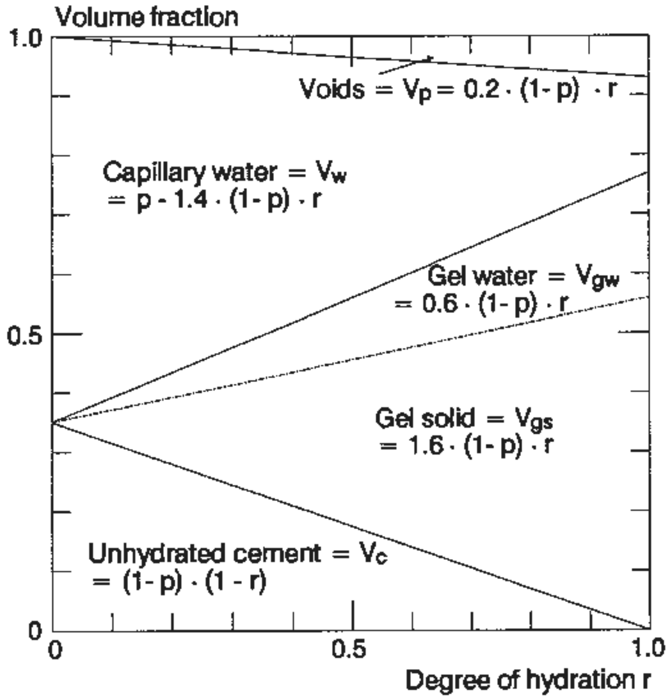


Figure 1

Density $= 1 - p$
$= 1/(1 + 3.11 \cdot w/c)$

Porosity $= p$
$= 3.11 \cdot w/c\,/(1 + 3.11 \cdot w/c)$

Water expands about 9% when it freezes. To avoid damage you need the pore volume to be at least 9% of the capillary water volume, i.e

$$V_p \geq 0.09 \cdot V_c$$

Using figure 1: phase transition of hardening cement paste, this transforms into

$$\frac{Q(M)}{Q_\infty} = r \geq 0.276 \cdot \frac{p}{1-p} \geq 0.86 \cdot \frac{w}{c}$$

If the measured reaction parameters of the adiabatic heat development are inserted, the theoretically necessary maturity (M) is found for obtaining of frost security during hardening of air-free cement paste without addition of water:

$$M \geq \tau_e/(-\ln(0.86 \cdot (w/c))^{1/\alpha}$$

This is illustrated in figure 2

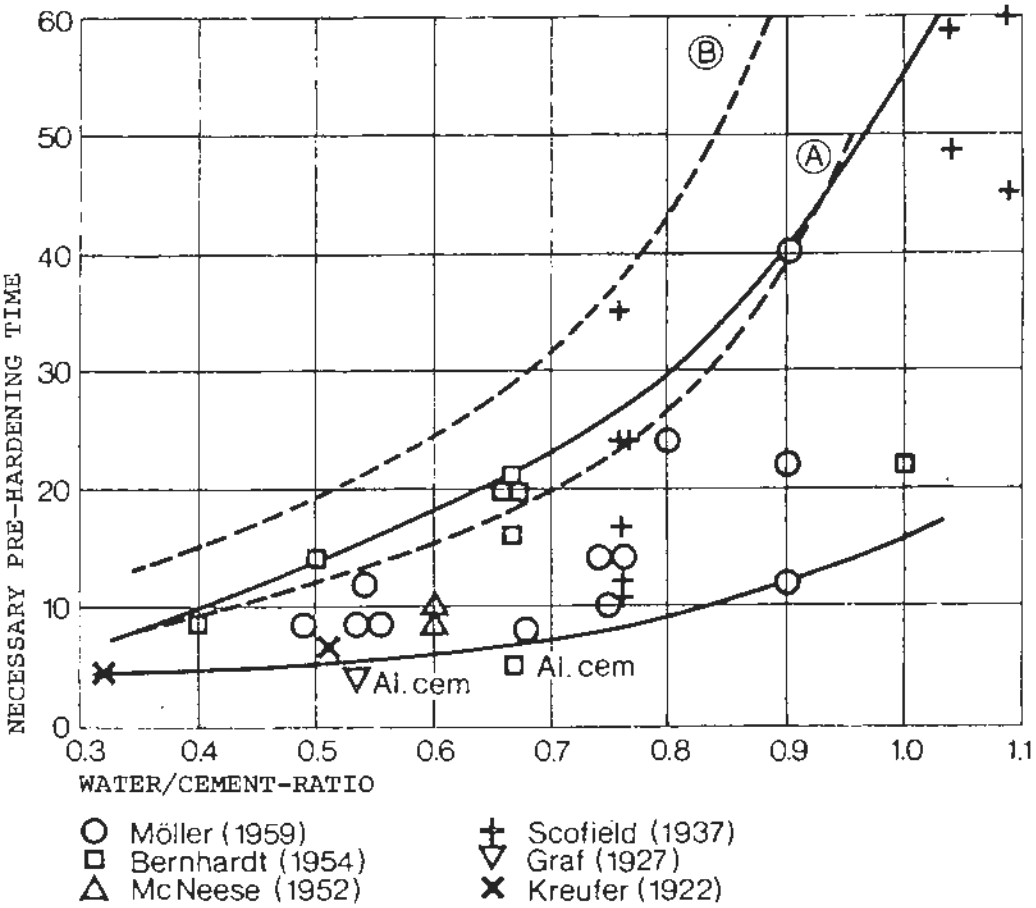


Figure 2

Necessary pre-hardening time (maturity at 20 °C) to obtain frost resistance of concrete due to self-desiccation. Maturity is shown as a function of water/cement-ratio. The dashed curves A and B are calculated from the equation using τ_e = 10 hours and 16 hours and α = 1.0.

3. Planning of construction by computer simulation

Symmetrical and non-symmetrical cross-sections

Casting of a one-dimensional symmetrical or non-symmetrical plane cross section, i. e. a wall or a bridge deck, may be planned by computer.

The results are graphically given as shown in figure 3 as the temperature development with time in the center and at the surface of the cross section, the maturity development with time in the concrete surface and the temperature profiles across the section at various times.

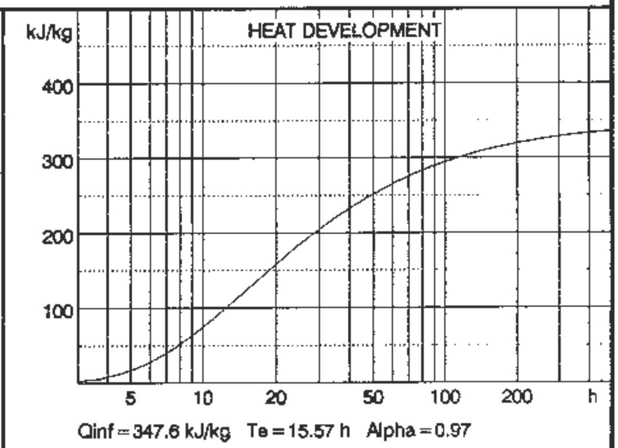
CIMS VERSION 1.2p DEMO
BKI, Postbox 82, DK2970, Hørsholm, Denmark

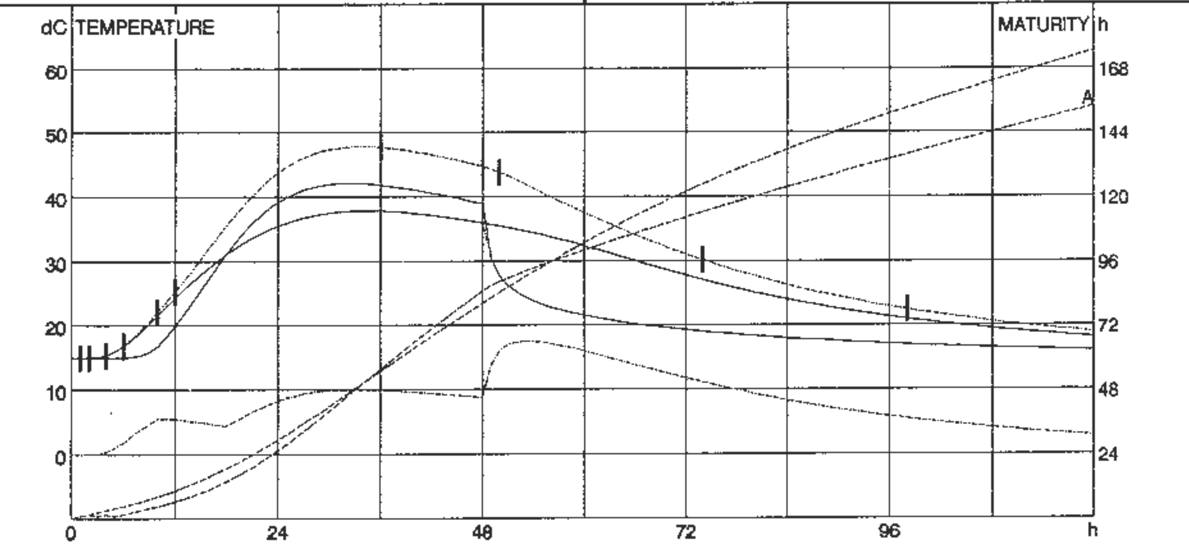
ASYMMETRICAL CROSS SECTION
Documentation sheet

Client:	NORDIC CONCRETE RESEARCH	Number:	1987
Name:	NCR	Date:	09-23-87
		Initials:	UK

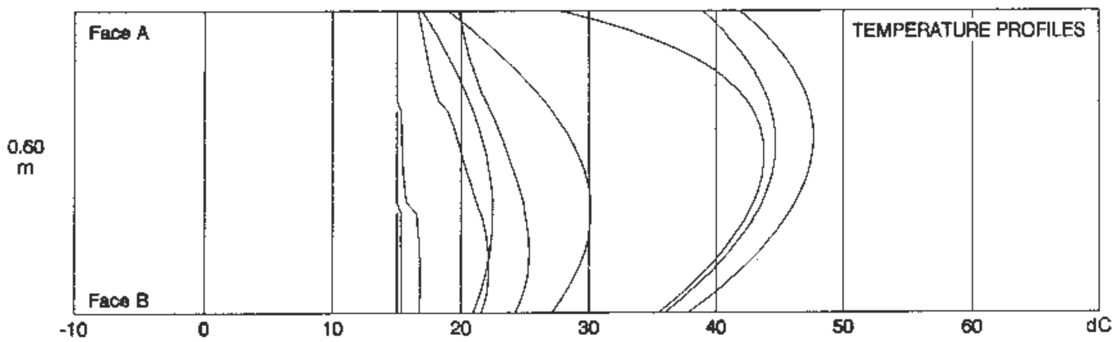
Time step	1.0	h
Cast step	2.0	h
Cast time	2.0	h
Cast height	0.20	m

		CONCRETE
Type		DEMO
Temp.	dC	15.0
Density	kg/m3	2447.9
Sp. heat	kJ/kg/dC	1.04
Th. cond.	kJ/m/h/dC	8.10
Cem. type		OPC
Cem. cont.	kg/m3	385.0





Tr. coef: 0.0/100.0 10.0/15.0 48.0/100.0
Air temp: 0.0/15.0



Tr. coef: 0.0/20.0
Air temp: 0.0/15.0

Figure 3
Documentation sheet for asymmetrical cross section

The non-symmetrical cross section only differs from the symmetrical by allowing different boundary conditions on the two concrete surfaces. This results in different maturities at the two surfaces and accordingly both maturities are shown.

Foundations

Casting of fresh concrete against hardened concrete or soil is treated in this simulation module. The difference from the 2 previous modules is that one concrete surface is cast against a physical structure possessing mass and heat capacitance. Accordingly, a layer of the soil is included in the calculations.

Often, foundations will be cast in layers with a definite time interval between layers. This possibility is included in the simulation.

4. Control at the building site

Measuring concrete temperature in the structure

Knowledge of the temperature development and temperature distribution in the hardening concrete will give the contractor an opportunity of controlling the hardening phase of the concrete in a safe and appropriate way.

On the basis of temperature measurements it is possible to make the necessary decisions as to stripping, stressing of cables, additional insulation, curing etc. so that prescribed requirements made in the actual work conditions are observed in a financially sound way.

In practice it has turned out to be appropriate to measure the temperature of the concrete by means of thermo-couples of the type copper/constantan which are placed in the prescribed positions before the casting is initiated.

The treatment of the measured results will to some extent depend on the purpose of the measuring. Usually, it will be a continuous control of the hardening process. Therefore it will be appropriate to assess the result after each reading and - if required - to correct the hardening process of the concrete.

Example

The practical application of CIMS is illustrated by an example:

A contractor wants to plan the casting of a 0.6 m wall. According to the time schedule it will be done in September. A concrete mix proportion is selected and the compressive strength development (figure 4) and the adiabatic heat development (figure 5) are determined in the site laboratory. The contractor decides to cast the wall in a wooden form. Experience tells him that the concrete mix temperature will be about 15^{o}C in September. He wants to strip the form after 24 hours according to the complete time schedule.

The following specifications must be met:

1) the temperature difference between the center and the surface of the wall must not exceed 20^{o}C
2) the concrete compressive strength at stripping of the form must be at least 15 MPa.

CIMS VERSION 1.2p DEMO BKI, Postbox 82, DK2970, Hørsholm, Denmark	STRENGTH DEVELOPMENT Documentation sheet

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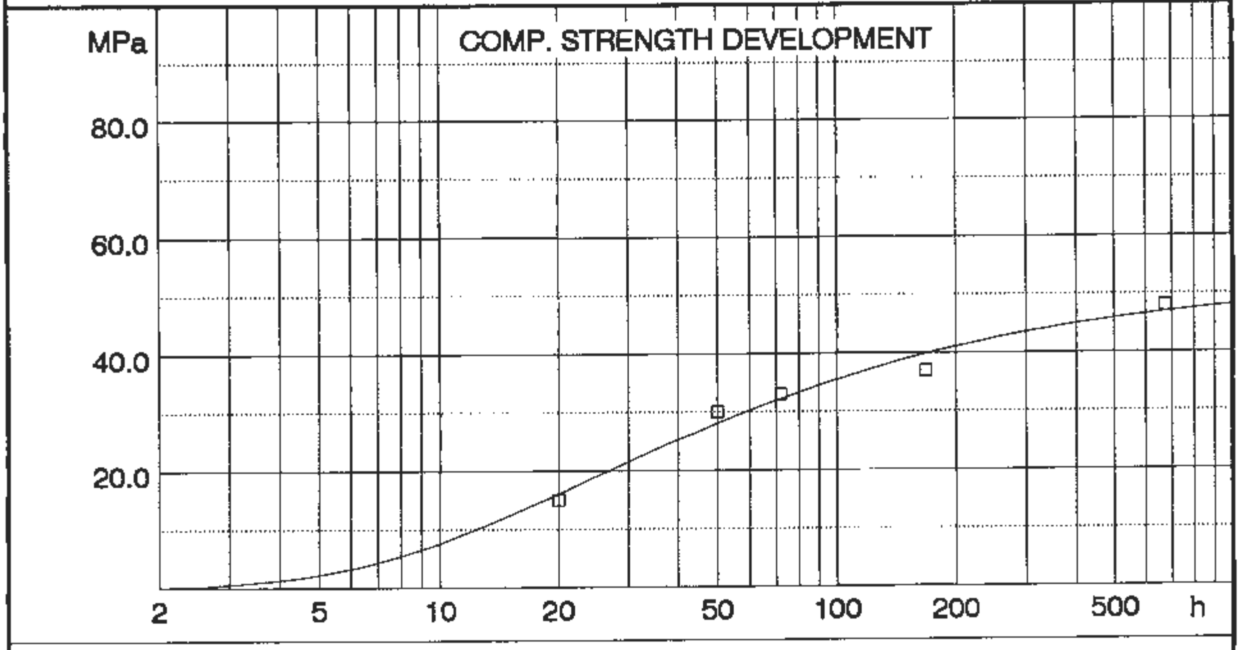
Name: NCR — Date: 09-23-87



CONCRETE: DEMO

LINEAR MODEL

So = 13.5 MPa To = 6.08 h

EXPONENTIAL MODEL

Sinf = 51.6 MPa Te = 24.85 h Alpha = 0.71

MIX MATERIALS	type	density kg/m3	weight kg/m3	volume m3/m3	comment
Water	TAP_WATER	1000.0	144.9	0.145	
Cement	OPC	3150.0	324.2	0.103	
Mineral additive	FLYASH	2200.0	60.8	0.028	
Aggregate	FINE_AGGREGATE	2630.0	759.9	0.289	
	GRANITE_2/8	2670.0	192.5	0.072	
	GRANITE_8/16	2688.0	289.8	0.108	
	GRANITE_16/32	2706.0	673.8	0.249	
Chemical Admixture	SUPER_PLAST	1190.0	2.0	0.002	
Air				0.005	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
kg/m3	kg/m3	kg/kg	%
2449.0	2447.9	0.41	0.5

COMMENTS:

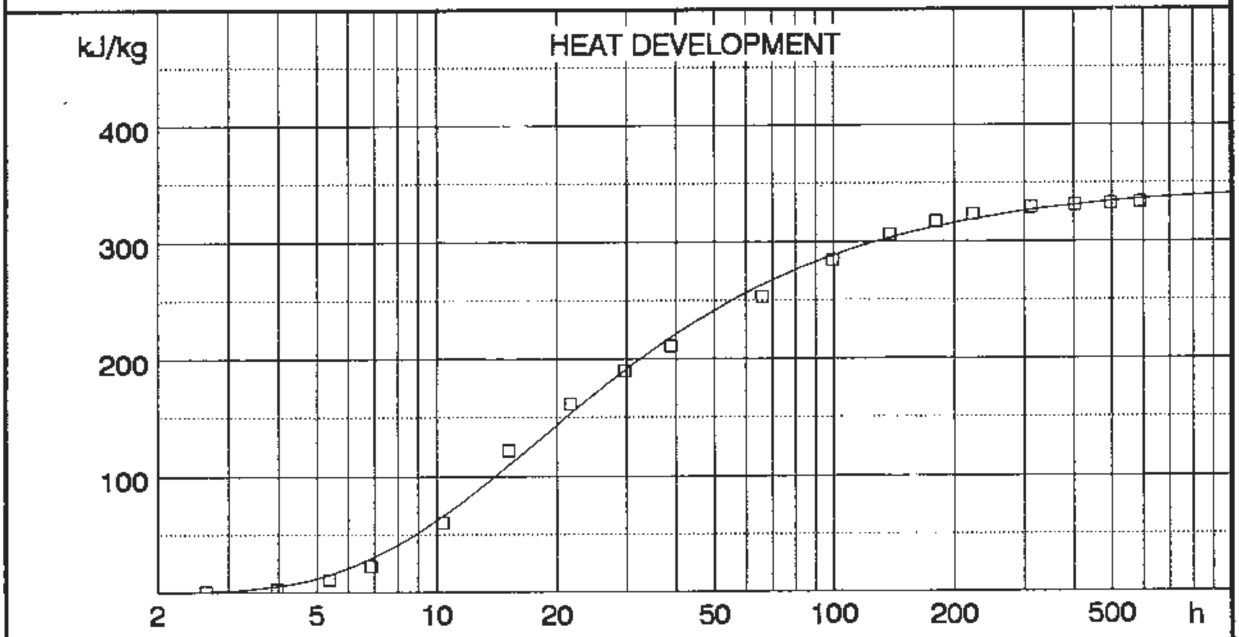
Figure 4

Documentation sheet for compressive strength development

CIMS VERSION 1.2p DEMO BKI, Postbox 82, DK2970, Hørsholm, Denmark	ADIABATIC CALORIMETRY Documentation sheet

Client: NORDIC CONCRETE RESEARCH Number: 1987 Initials: UK

Name: NCR Date: 09-23-87



CONCRETE: DEMO Cement + min. additives Specific heat: 1.04 kJ/kg/dC

LINEAR MODEL
Qo = 123.6 kJ/kg To = 6.24 h

EXPONENTIAL MODEL
Qinf = 347.6 kJ/kg Te = 17.57 h Alpha = 0.97

MIX MATERIALS	type	density kg/m3	weight kg/m3	volume m3/m3	comment
Water	TAP_WATER	1000.0	144.9	0.145	
Cement	OPC	3150.0	324.2	0.103	
Mineral additive	FLYASH	2200.0	60.8	0.028	
Aggregate	FINE_AGGREGATE	2630.0	759.9	0.289	
	GRANITE_2/8	2670.0	192.5	0.072	
	GRANITE_8/16	2688.0	289.8	0.108	
	GRANITE_16/32	2706.0	673.8	0.249	
Chemical Admixture	SUPER_PLAST	1190.0	2.0	0.002	
Air				0.005	

CONCRETE PROPERTIES

density measured	density calculated	w/c-ratio	air content
kg/m3	kg/m3	kg/kg	%
2449.0	2447.9	0.41	0.5

COMMENTS:

Figure 5

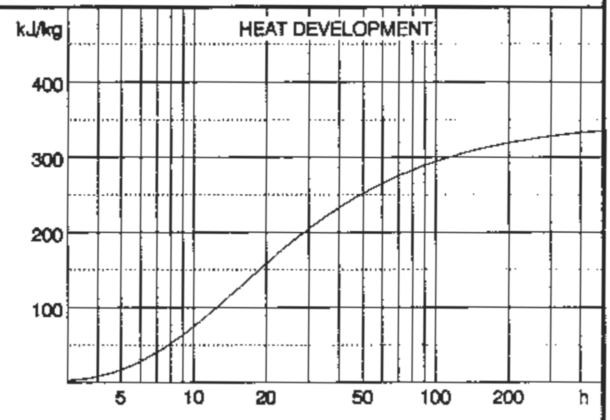
Documentation sheet for heat development

CIMS VERSION 1.2p DEMO	SYMMETRICAL CROSS SECTION
BKI, Postbox 82, DK2970, Hørsholm, Denmark	Documentation sheet

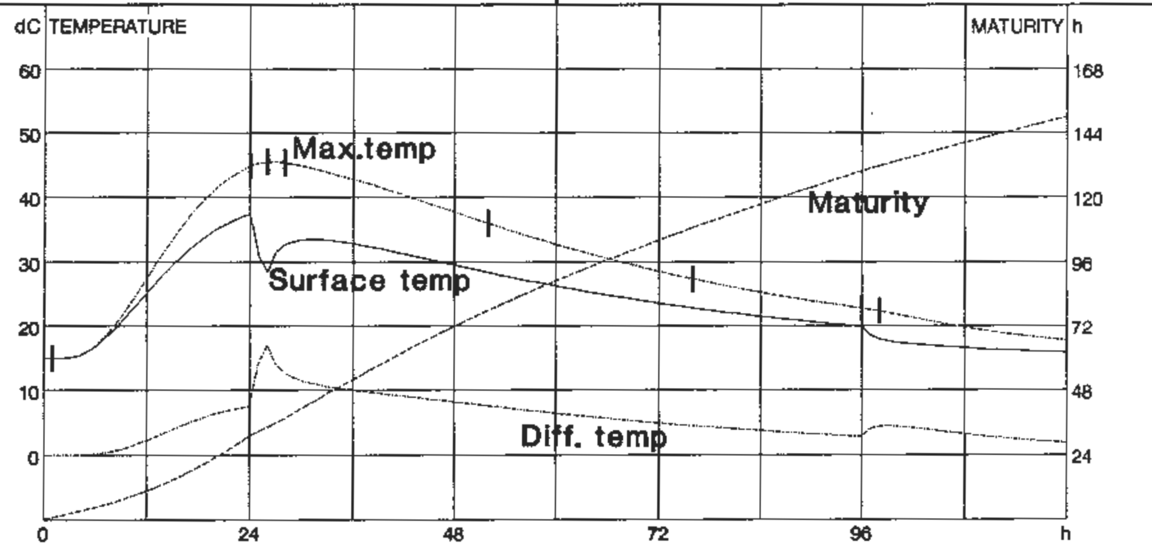
Client:	NORDIC CONCRETE RESEARCH	Number:	1987	Initials:	UK
Name:	NCR	Date:	09-23-87		

Time step	1.0	h
Cast step	0.0	h
Cast time	0.0	h
Cast height	0.60	m

		CONCRETE
Type		DEMO
Temp.	dC	15.0
Density	kg/m3	2447.9
Sp. heat	kJ/kg/dC	1.04
Th. cond.	kJ/m/h/dC	8.10
Cem. type		OPC
Cem. cont.	kg/m3	385.0



Qinf = 347.6 kJ/kg Te = 15.57 h Alpha = 0.97



Tr. coef: 0.0/20.0 24.0/100.0 26.0/30.0 96.0/100.0

Air temp: 0.0/15.0

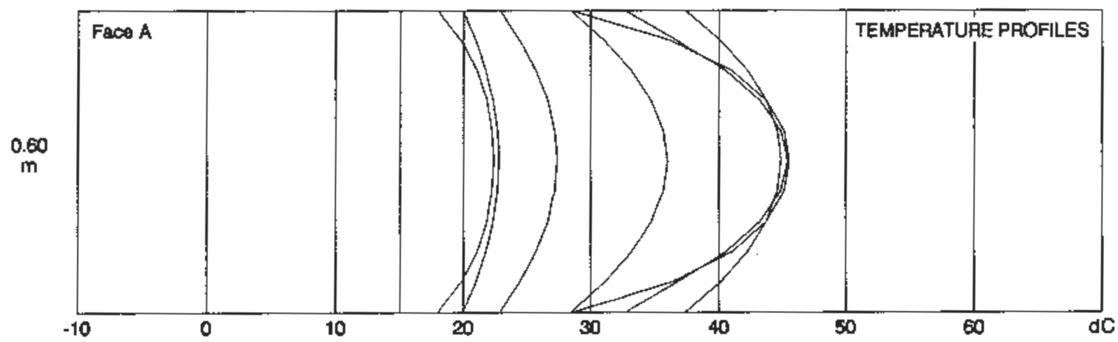


Figure 6

Documentation sheet for simulation of symmetrical cross section.

The simulation results are shown in figure 6. From this it is seen that the first specification is met, if the wall is insulated by plastic foil after removal of the form. At this time (26 hours after casting) the maximum temperature difference is about 17°C.

The plastic foil is removed 4 days after casting. The concrete maturity at the surface at the time of stripping the form is about 28 hours. According to figure 4 this corresponds to a compressive strength of about 21 MPa.

Notations

e	=	thickness of form/insulation (m)
m_k	=	convection coeff. of thermal resist. ($m^2 \cdot h \cdot {}^oC/kJ$)
p	=	porosity (m^3/m^3)
t	=	time (h)
v	=	wind velocity (m/s)
V_c	=	rel. volume of capillary water (m^3/m^3)
Vp	=	rel. volume of capillary pores (m^3/m^3)
w/c	=	water/cement - ratio (kg/kg)
r	=	degree of reaction
E	=	activation energy (J/mole)
H	=	temperature function (rel. velocity)
R	=	gas constant (J/mole · °C)
M_{20}	=	maturity = eq. age at 20°C (h)
Q	=	heat developed (kJ/kg)
Q_∞	=	total heat development for M_∞ (kJ/kg)
α	=	curvature parameter (-)
cot_k	=	convective coeff. of thermal transmittance ($kJ/m^2 \cdot h \cdot {}^oC$)
σ	=	compressive strength (MPa)
σ_∞	=	potential final strength for M_∞ (MPa)
λ	=	thermal conductivity (kJ/m · h · °C)
Θ	=	temperature (°C)
τ_e	=	characteristic time constant (h)

Remark : 1 kJ/h = 3.6 kW/s

Reference:

/1/ Hansen, P. Freiesleben & Pedersen, E. J.: "Curing of concrete structures", Appendix 1, CEB Bulletin d'information No 166, 1985, pp. 42.