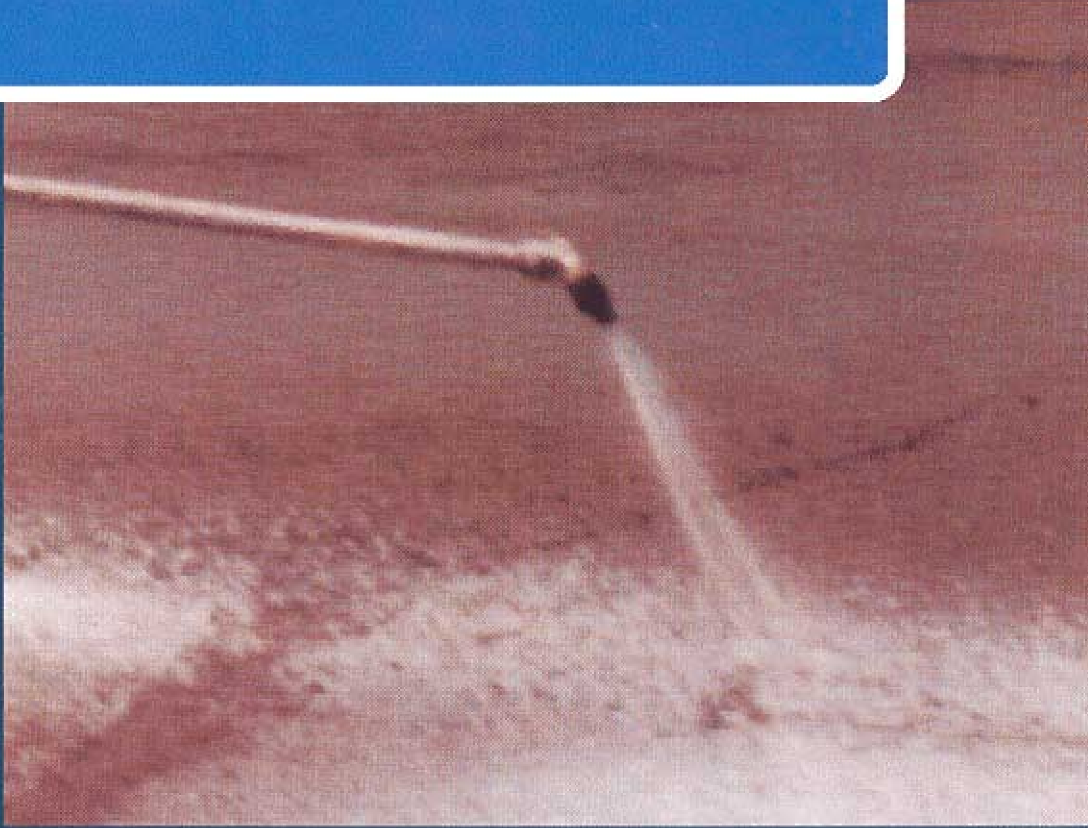
HETEK

Curing Guideline



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Abstract

This report forms a part of the Danish Road Directorate's research programme called High Performance Concrete - The Contractor's Technology (abbreviated to HETEK). HETEK is divided into eight parts in which Part No. 6 concerns Curing. Part No. 6 includes State of the Art, Supplementary Research, Phases 1 to 4, Main Report and Guidelines.

This report presents commonly used requirements on curing of concrete, and it may function as a manual on practical handling of curing problems. It also presents a few examples of handling curing problems in practice.

A main requirement on curing prescribes the amount of water allowed to evaporate before curing must be started. This amount depends on the concrete's content of mineral admixtures. This requirement can be met by a theoretical calculation or by reading diagrams based on the wind velocity, relative humidity and temperature of concrete and air. If the requirement is not met in one of these ways, the curing must start within a short period, specified as a number of hours after casting. Another main requirement concerns the length of the period before the curing can be stopped. This requirement depends on the environmental class and on the degree of hydration, which in turn can be evaluated from the maturity hours.

Various curing techniques have been mentioned. They include commonly used methods like keeping the concrete in mould, adding curing membranes or curing compounds, keeping the surface wet or controlling the climate. Adding admixtures or fibres to the concrete is also mentioned as a possibility. A few examples have been included to present the calculation of degree of reaction, maturity and the starting time and duration of curing. A set of forms to facilitate the process of planning, inspection and documentation of the curing is given in appendices as well as examples of their use.

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0. Preface

This project regarding curing is part of the Danish Road Directorate's research programme, High Performance Concrete - The Contractor's Technology (in Danish: Højkvalitetsbeton - Entreprenørens Teknologi) abbreviated to HETEK.

High Performance Concrete is concrete with a service life in at least 100 years in an aggressive environment.

The research programme includes investigations regarding the contractor's design of high performance concrete and execution of the concrete work with reference to obtain the requested service life of 100 years.

The research programme is divided into seven parts within the following subjects:

- chloride penetration
- frost resistance
- control of early-age cracking
- compaction
- curing (evaporation protection)
- trial casting
- repair of defects

The Danish Road Directorate has invited tenders for this research programme which primarily is financed by the Danish Ministry for Business and Industry - The Commission of Development Contracts.

This project regarding curing is performed by:

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The aim of this report is to give guidelines on how to prevent plastic shrinkage cracks in concrete surfaces and to ensure that sufficient water remains in the concrete, so that the development of its properties will take place in the desired way.

The guidelines include sections about planning, performance, inspection and documentation of the curing in practice. The subjects are:

- Demands on the starting time of the curing.
- Demands on the length of the curing period
- Information about and evaluation of various curing methods
- Planning the curing process
- Inspection of the curing process
- Documentation of the curing

The requirements on curing will be dealt with in chapter 2. The chapter also presents examples on calculation of the degree of reaction, the setting time and the evaporation under given climate conditions. The evaporation can also be read from graphs in appendix 1.

In chapter 3 various curing methods are described and evaluated. Appendix 2 presents an overview of the methods.

Chapter 4 deals with planning and inspection of curing. Forms for planning, inspection and documentation are given in appendix 3.

Chapter 5 presents a few examples of how the curing can be planned.

The results of the project is published in the following reports:

HETEK - Curing - State of the Art
HETEK - Curing - Supplementary Research - Proposal
HETEK - Curing - Phase 1: Laboratory Tests
HETEK - Curing - Phase 2: Evaluation of Test Results
HETEK - Curing - Phase 3: Verification Tests
HETEK - Curing - Phase 4: Final Evaluation and Definition of Conformity Criteria
HETEK - Curing - Main Report
HETEK - Curing - Guidelines.

April 1997
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Steering Committee of HETEK-Curing project

1. Introduction

The term hardening technology stands for a general description of the chemical and physical reactions between portland cement and puzzolans (such as fly ash and micro silica) in concrete. The hardening process can be controlled by means of the temperature and the humidity. This report only deals with controlling the humidity of the concrete.

Concrete is vulnerable during the early phase after casting. In this phase some water will evaporate from free surfaces which in turn will introduce tensile stress and cracks in the surface. If the water loss is not controlled in a proper way, plastic shinkage cracks in the surface may be the result. The water in the concrete is of crucial importance to the reactions between cement, puzzolan and water and thereby to the development of the desired qualities of the concrete. It is therefore important to control the loss of water caused by evaporation.

Draft proposal DS 482 "Execution of concrete structures", march 1997, contains requirements on the starting time of curing in order to prevent cracks from plastic shrinkage. The requirements depend on the content of fly ash and microsilica, because different types of concrete have different sensitivities to evaporation of water and consequently different risks to form cracks by plastic shrinkage. The requirements are mentioned in detail in section 2.1.

The number of plastic shrinkage cracks is increased by an increased evaporation in the fresh concrete, in which the evaporation primarily depends on the climate around the concrete and on the temperature of the concrete. In section 2.5 is described how the evaporation rate can be calculated based on the wind velocity, the relative humidity of the air and the temperature of concrete and air. The calculations can be carried out by means of the nomograms for reading the amount of evaporated water as a function of time at typical weather conditions, see appendix 1.

Draft proposal DS 482 "Execution of concrete structures", march 1997, also contains requirements on the period in which the concrete has to be protected from drying out. The aim of this is to ensure that a sufficient amount of water remains in the concrete, so that it can be part of the hydration process and thereby in development of the desired properties. The requirements on the length of the curing period are found in section 2.2.

In planning and controlling the hydration process it may be necessary to know the degree of reaction at a given point of time as well as the setting time. This knowledge can be evaluated from a graph of the heat development of the concrete as mentioned in section 2.4.

Drying out by evaporation is prevented most efficiently by covering the surface in some way. It can be done by keeping the concrete in the mould, by covering it with plastic films, tarpaulins, mats of polystyrene foam etc. The concrete surface can also be sprayed with a curing compound or water in the early phase. Finally, polymeric admictures or fibres can be added to the concrete during mixing, but the effect of such measures is not well documented.

These kind of curing methods are mentioned and evaluated in chapter 3. Demands on the efficiency of curing compounds are mentioned in section 2.3.

Appendix 2 presents an overview of curing methods.

The aim of planning the hydration is to be able to evaluate different methods and prescribe appropriate methods to be used from the time of casting until the end of the curing period. Different concretes, moulds and curing methods are considered in the process of planning. In order to find the best solution, technically and economically, different alternatives have to be discussed as done in chapters 4 and 5.

When the curing is planned it is necessary to have an estimate of the development of maturity in the surface of the concrete. The development of maturity can be simulated by computer calculations, as described in examples in chapter 5

Inspection includes control and documentation of the curing process. This is mentioned in section 4.2.

Appendix 3 includes forms to be used in planning, inspection and documentation to verify that the requirements on starting time and curing period are met.

In addition to the requirements on curing during the hardening period other requirements are put on the concrete, e.g., demands on maximum temperature differences, relative stresses, the strength at the time of demoulding and frost resistance.
Of course, such requirements are to be met at the same time as those mentioned in this report. Further information on this subject can be found in [8] and [9].

1.1 Object

This report is mainly intended for contractors to use as a tool to optimize the planning and controlling the hydration process. The guidelines included should be easy to use with the forms, diagrams and formulas that are illustrated by examples and instructions.

1.2 Background

The guidelines are written with reference to the following literature [1]-[6], see the List of Literature.

[1] HETEK, Curing, State of the Art
Summary of relevant, exsisting literature and previous investigations.

[2] HETEK, Curing, Phase 1, Laboratory Tests
Laboratory tests in which concrete specimens were subjected to controlled values of temperature, relative humidity and wind velocity while the loss of water by evaporation was measured continuously. The tests were performed in a climatically controlled wind tunnel in DTI's laboratory. This equipment was developed to investigate the effect of different curing methods on the quality of concrete surfaces. The principles behind the test method can be found in DTI's test method TI-B 33 (1992): "Measurement of the

efficiency of curing compound".

The following curing methods have been investigated:
- Curing in moulds of varnished plywood
- Curing by means of plastic films, curing compound and wetting
- No curing at all, i.e., free surface

The quality of the surfaces of the test specimens was described on the basis of the following measurements:

- Micro structure, i.e., number, size and orientation of cracks
- Chloride permeability
- Capillary water absorption
- Carbonation depth, accelerated test

[3] HETEK, Curing, Phase 2, Evaluation of Test Results
The test results from Phase 1 were evaluated and related to the structure density of the cement paste. The curing methods were ranked according to the test results.

[4] HETEK, Curing, Phase 3, Verification Tests
10 additional curing tests were performed, 4 in DTI's laboratory and 6 in the field.

[5] HETEK, Curing, Phase 4, Final Evaluation and Definition of Conformity Criteria
General evaluation of the results from Phase 1 and 3. The results were related to the existing conformity criteria.

[6] HETEK, Curing, Main Report
Summary report on the tests performed, the results and the conclusions from the Phases 1-4 and these Guidelines.

2. Requirements on Curing

Section 2.1 and 2.2 specify the requirements on the required starting time and length of the curing period. The requirements are found in Draft proposal DS 482 "Execution of concrete structures", march 1997.

Section 2.3 specifies requirements on the efficiency of curing compounds when they are used to reduce the loss of water by evaporation.

Section 2.4 specifies requirements concerning the degree of reaction and setting time.

Section 2.5 specifies methods to calculate the amounts of water lost by evaporation as a function of time. In appendix 1 graphs are presented in which similar values can be read under typical climatic conditions.

2.1 Starting time of curing

In the passive environmental class the requirements on curing in section 2.1 (starting time) and 2.2 (curing period) must only be met if it is required by the project material.

Unless other opportunities have shown to give better results, the curing must be started before evaporation of the amounts of water mentioned in table 2.1.

FA + MS, maximum weight-% of the binder	MS, maximum weight-% of the binder	Maximum amount of water evaporated before curing kg/m^2
35	10	1.5
15	5	3.0
5	0	6.0

Table 2.1. Requirements on maximum amount of water evaporated before curing is started

The curing must be started not later than 1 maturity hour after setting time.

If the requirements in table 2.1 are not met and documented, curing of the surfaces must be started before the times since casting mentioned in table 2.2 have elapsed.

FA + MS, maximum weight-% of the binder	MS, maximum weight-% of the binder	Outdoors	Indoors		
			Concrete temperature		
			< 15°C	15-30°C	≥ 30°C
35	10	1 hour	2 hours	1.5 hour	1 hour
15	5	2 hours	4 hours	3 hours	2 hours
5	0	4 hours	8 hours	6 hours	4 hours

Table 2.2. Requirements on starting time for curing after casting outdoors and indoors.

The required starting times in table 2.1 are valid if the thickness of the concrete layer is equal to or greater than 0.2 m. If the layer is less than 0.2 m, the required starting time must be reduced in proportion to the thickness.

If treatment of the concrete surface is planned to take place after the curing has been established it must be established temporarily.

2.2 Curing period

Unless other alternatives have shown to give better results, the curing must be continued until the degrees of reaction mentioned in table 2.3 are obtained in the surface layer of the concrete (documented by measurement of the maturity in a depth not greater than 10 mm).

Environmental class	Passive	Moderate	Aggressive	Extra aggressive
Degree of reaction R (%)	40	60	85	90

Table 2.3. Minimum degree of reaction that has to be obtained before curing can be stopped

If the requirements in table 2.3 are not met and documented, the curing must be continued until the maturities mentioned in table 2.4 have been obtained (documented by measurement of the maturity in a depth not greater than 10 mm).

	Necessary age of concrete before curing can be stopped (maturity hours)			
Environmental class	Passive	Moderate	Aggressive	Extra aggressive
w/c > 0.55	15	-	-	-
0.55 ≥ w/c > 0.45	15	36	-	-
0.45 ≥ w/c > 0.40	12	24	120	-
0.40 ≥ w/c	12	24	96	120

Table 2.4. Requirements on the maturity of the concrete which has to be obtained before curing can be stopped

If the setting time of the concrete is more than 5 hours, the required maturities mentioned in table 2.4 must be increased with a similar number of hours.

2.3 Efficiency

As a means to reduce the evaporation of water from a fresh concrete surface a curing compound is often used, which is a thick fluid. The efficiency of the curing compound must be at least 75% which means that it must reduce the amount of water evaporated from a fresh concrete surface by at least 75% of the amount evaporated from a similar, but free surface.

The efficiency of the curing compound is tested by DTI's test method TI-B 33. The curing compound is tested on a concrete prescribed in the test standard. Six samples of the concrete are cast, and three of them are sprayed with the curing compound being tested. Then the weight loss from the concrete surfaces is recorded continuously in a wind tunnel with constant wind velocity, temperature and relative humidity.

2.4 Concrete

In the initial, plastic state after casting and vibration a separation may take place, where the heavy components (aggregates and cement paste) move downwards and the light component water moves towards the surface. This water separation is called bleeding.

The evaporation from the concrete surface depends on the climate. If the evaportion is faster than the bleeding, the concrete will dry out in the surface and shrinkage cracks may be the result. Plastic shrinkage cracks are a result of tensile stresses caused by a lowering of the water vapour pressure over curved water surfaces in the soncrete surface. When the water vapour pressure falls, the relative humidity becomes lower than 100% in the concrete surface.

The greater the resistance to water movements is in a plastic concrete, the greater is the risk of getting cracks caused by plastic shrinkage. The water movements in concrete are reduced when fly ash and micro silica are added. Micro silica is much finer grained than the cement and the fly ash, and it has the greatest reducing impact on water movements.

Even if some bleeding might be expected to reduce the amount of cracks, caused by plastic shrinkage, the phenomenon reduces the strength of the surface layer because of its high water/cement ratio.

At a certain value of evaporation of water an increased binder content in relation to the water content will usually increase the tensile stresses in the surface of the concrete, as the pores becomes finer caused by a lower water/cement ratio [7].

This is the reason why the requirements on the amounts of water allowed to evaporate before curing is started also depend on the content of fly ash and micro silica.

The concrete must reach a sufficient degree of reaction before a covering material put on top of the concrete can be removed, because water must be present in the concrete. Water is necessary to ensure a proper reaction between cement and puzzolans and thereby obtain a sufficient structure density and strength. Furthermore, as the impact from the environment on the concrete is gradually increased, the curing periods must be increased accordingly.

2.4.1 Degree of reaction

The length of the curing period can be related to the degree of reaction of the concrete. The degree of reaction is the ratio of the amount of reacted binder to the total amount of binder.

The degree of reaction can be evaluated on the basis of measurement of the adiabatic heat development Q(M) as a function of the maturity M. A mathematic formula to describe Q(M) is given by equation (2.1) and an example of a graph of Q(M) is shown as a S-shaped graph in figure 2.1.

$$Q(M) = Q_\infty \cdot \exp\left(-\left(\frac{\tau_e}{M}\right)^{\alpha}\right) \quad \text{[kJ/kg binder]} \qquad (2.1)$$

in which :

Q_∞ Total heat development [kJ/kg binder]

τ_e Time constant [hours].
Q(M) has the steepest tangent at $M = \tau_e$, (the sloping line in figure 2.1)
A reduced value of τ_e increases the velocity of heat development.

α Curvature parameter. The steepness of the S-shaped graph increases with increasing values of α

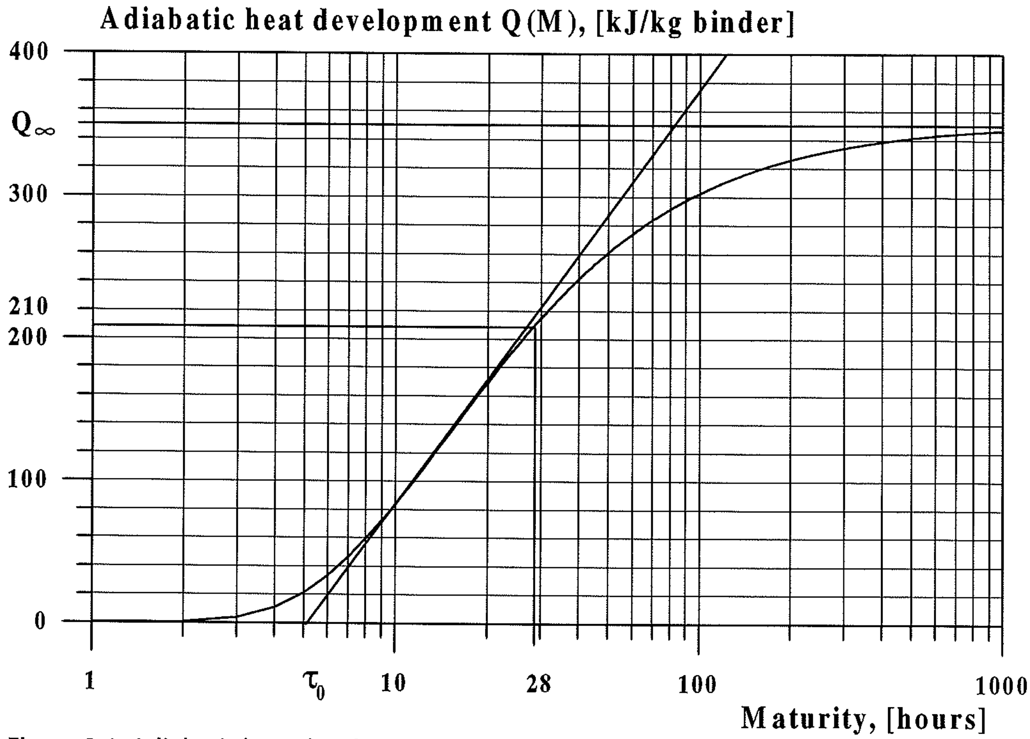


Figure 2.1. Adiabatic heat development as function of maturity shown as the S-shaped function.

Normally the contractors present results from measurements of heat development of concrete in a form where the values Q_∞, τ_e and α to be used in the formula (2.1) are included.

In the following two examples it is demonstrated, how the length of the curing period can be evaluated when a certain degree of reaction R is required. The curing period can be evaluated from the heat development either by a graphic method (example 2.1) or by calculation (example 2.2).

Example 2.1: Curing period, graphic method

The curing period is to be estimated for a concrete in moderate environmental class. Table 2.3 shows that the requirement on the curing period is a degree of reaction R = 0.6 of the concrete.

The heat development is evaluated from figure 2.1. The total heat developed is $Q_\infty = 350$ kJ/kg binder, so 0.6 in degree of reaction is reached when a heat development Q = 210 kJ/kg binder is obtained, see formula (2.2).

$$R = \frac{Q(M)}{Q_\infty} \Rightarrow Q(M) = R \cdot Q_\infty = 0{,}6 \cdot 350 = 210 \text{ kJ/kg} \qquad (2.2)$$

By drawing a horizontal line at this level up to the graph, it is seen that the required degree of reaction R = 0.6 will be obtained at 28 maturity hours.

This means that the chosen type of curing, mould, plastic film, mats, etc., cannot be removed before 28 maturity hours after casting.

Example 2.2: Curing period, calculated.
When the parameters τ_e and α to describe the heat development are known, then formula (2.3) can be used to calculate the value of the maturity M which is necessary to reach a given degree of reaction R.

The concrete producer has stated the following values: τ_e = 13.4 hours and α = 0.9. The requirements on the curing period is that a degree of reaction R = 0.6 must be obtained. Formula (2.2) has been inverted and formula (2.3) is found. By entering the values τ_e = 13.4 hours and α = 0.9 in this formula, the required maturity M = 28 hours is found.

$$R = \frac{Q(M)}{Q_\infty} = \frac{Q_\infty \cdot \exp(-(\frac{\tau_e}{M})^\alpha)}{Q_\infty} = \exp(-(\frac{\tau_e}{M})^\alpha) \Rightarrow$$

$$M = \frac{\tau_e}{(-\ln(R))^{1/\alpha}} = \frac{13.4 \text{ hours}}{(-\ln(0.6))^{1/0.9}} = 28 \text{ hours} \qquad (2.3)$$

The conclusion is that 28 maturity hours must have elapsed before the curing can be stopped, when a degree of reaction 0.6 is required (this result is of course the same as that found in example 2.1).

2.4.2 Setting time

The term setting time is used to describe the period after casting in which the concrete can be vibrated, depending on the climatic conditions. Danish Standard DS423.17 specifies how the setting time is determined.

The setting time of concrete can be estimated to be equal to the value of the parameter τ_0 (hours) which is one of the parameters used to describe the graph of heat development. τ_0 can be evaluated from an S-shaped graph, like that in figure 2.1, in the folowing manner: The steepest point of the graph is found, and at this point the tangent of the graph is drawn and intersected with the maturity axis. τ_0 is the maturity read in the intersection point. In figure 2.1 the value τ_0 = 5 maturity hours is found.

The following example demonstrates that the setting time of concrete can influence the length of the curing period.

Example 2.3: Setting time of concrete and curing period
If a concrete with equivalent w/c = 0.4 for use in extra aggressive environment is chosen, table 2.4 shows that the curing can be stopped at 120 maturity hours.

The heat development has been measured and shown in a graph like that in figure 2.1. The steepest tangent is drawn and the setting time is found to be $\tau_0 = 8$ maturity hours. However, the maturity hours in table 2.4 are based on the assumption that the setting time is less than 5 maturity hours. So in this case the curing time has to be increased by a number of hours corresponding to the difference, see formula (2.4).

$$\text{Curing period} = 120 + (8 - 5) = 123 \text{ maturity hours} \tag{2.4}$$

The result is that the curing period must be increased into 123 maturity hours.

2.5 Climate

The climate surrounding a concrete has a great influence on the amount of water lost by evaporation from the concrete during a given period. Therefore, some of the requirements on the starting time of the curing are requirements on the allowable amount of water which has evaporated before curing must be started, see table (2.1).

This chapter describes a procedure to calculate the loss of water by evaporation from a fresh concrete when a certain climate is assumed. The first part of the calculation procedure is based on figure 2.2 which is a nomogram for calculating the evaporation rate of water from a wet concrete surface.

Below follows an example of calculating water loss by evaporation.

Example 2.4: Water loss by evaporation
Assume that a concrete floor with a thickness of 0.15 m is cast indoor in a building where the temperature is 25°C and the relative humidity is 70 %.

The concrete used contains 20 % fly ash and 7% micro silica, and with this concrete the requirement found in table 2.1 is that only 1.5 kg/m² of water is allowed to evaporate before curing must be started (provided the thickness of the concrete is 0.2 m).

a) The temperature of the concrete surface was measured to be 27°C. The relative humidity of the concrete surface can be assumed to be 100%. The point A (27°C, 100%) in the upper part of the nomogram in figure 2.2 gives the water vapour pressure $P_{concrete} = 3.6$ kPa in the surface of the concrete.

b) The air temperature in the building was 25°C, and the relative humidity was 70%. Point B(25°C,70%) in figure 2.2 gives the water vapour pressure $P_{air} =$ 2.2 kPa in the indoor air.

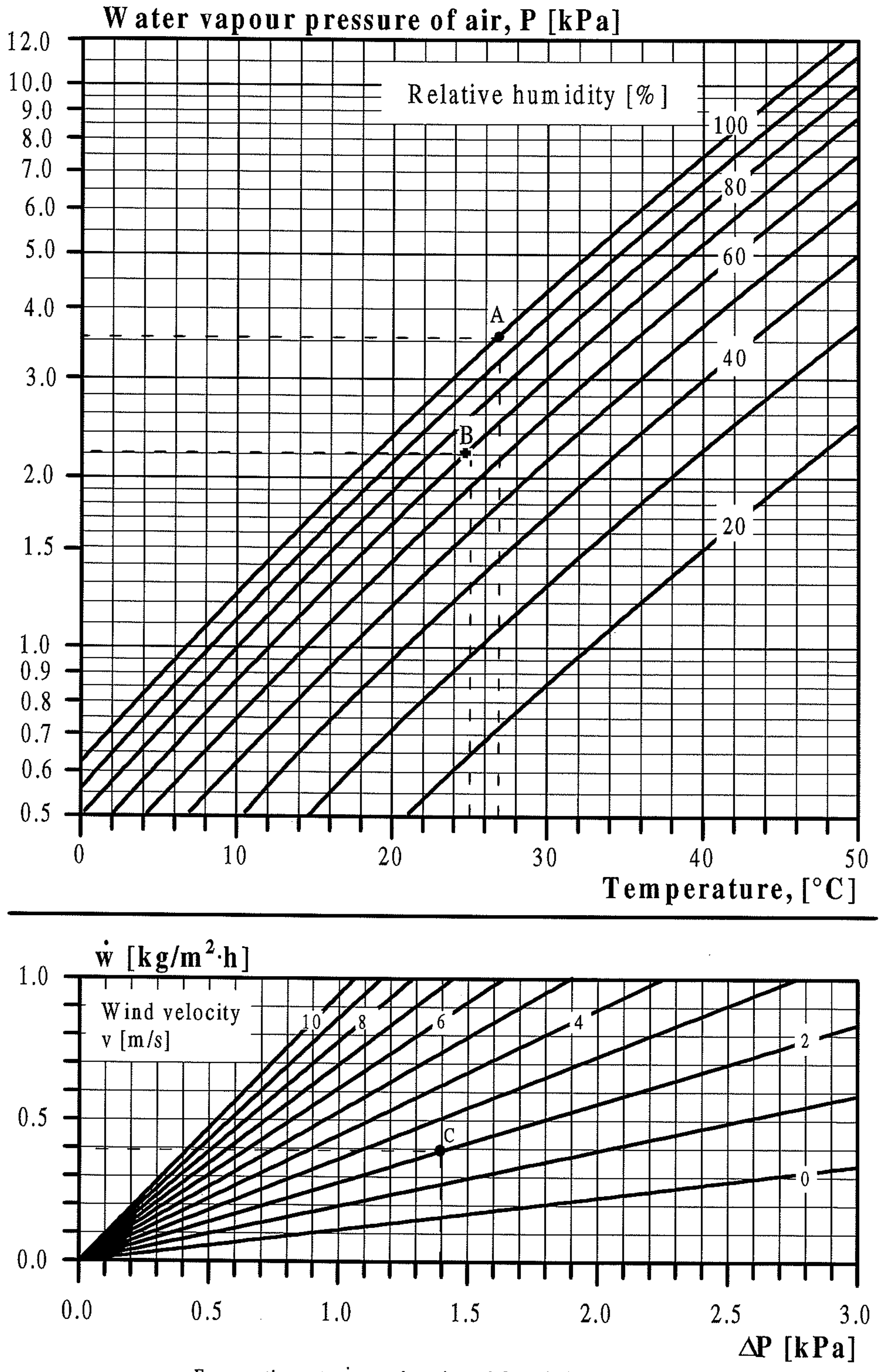
c) The difference in vapour pressure ΔP between concrete and air is calculated by $\Delta P = P_{concrete} - P_{air} = 3.6 - 2.2 = 1.4$ kPa. The wind velocity in the building is evaluated to be v = 2 m/s. With these values it is found in the lower part of the nomogram in figure 2.2 (point C) that the evaporation rate is w = 0.4 kg/m²h.

d) The time period from casting to curing start is then calculated by the expression:

$$\text{Time} = \frac{\text{Evaporated water}}{\text{Evaporation rate}} = \frac{1.5\ \text{kg/m}^2}{0.4\ \text{kg/m}^2 \cdot \text{h}} = 3.75\text{hours} \qquad (2.5)$$

e) As the concrete thickness is smaller than 0.2 m, the time period before curing must be reduced in proportion to the thickness of the actual concrete, see formula (2.6)

$$\text{Time} = \left(\frac{0.15\ \text{m}}{0.2\ \text{m}}\right) \cdot 3.75\ \text{hours} \approx 2.8\ \text{hours} \approx 2\ \text{hours} + 50\ \text{minutes} \qquad (2.6)$$



Evaporation rate $\dot{w}$ as a function of the wind speed v and water vapour pressure difference ΔP, is calculated from the expression:

$$\dot{w} = (0.113 + 0.083 \cdot v) \cdot \Delta P \quad [kg/m^2 \cdot h]$$

Assumption: Wett surface ~ until 10 - 20 maturityhours.

Figure 2.2. Nomogram for calculation of rate of evaporation of water from fresh concrete.

In order to evaluate the evaporation rate from fresh concrete the wind velocity, the air temperature and relative humidity are required.

In long term planning typical values of temperature and relativ humidity must be used. Values found in table 2.6 can be used (based on Statistical Yearbook, Copenhagen,1996). The wind velocities are weekly averages from Denmarks Meteorological Institute.

When outdoor castings are planned, it is necessary to verify, immediately before casting, that assumptions about the weather are still valid and adjust the planned curing in accordance to any new situation.

The public weather forecast may be used to do short term predicions of the weather. As an aid in transforming the messages from the public service into wind velocities, table 2.5 can be used.

Wind force	Wind velocity [m/s]	Effect
Calm	0 - 0.2	Vertical smoke columns
Light air	0.3 - 1.5	Neat vertical smoke columns
Light breeze	1.6 - 3.3	Leaves move, flags move gently
Gentle breeze	3.4 - 5.4	Twigs move, flags move
Moderate breeze	5.5 - 7.9	Pieces of paper are lifted
Fresh breeze	8.0 - 10.7	Small trees sway
Strong breeze	10.8 - 13.8	Big branches move
Near gale	13.9 - 17.1	Big trees move
Gale	17.2 - 20.2	Twigs and branches break
Strong gale	20.8 - 24.4	Big trees sway, big branches break
Storm	24.5 - 28.4	Trees are pulled up, cosiderable damages on buildings
Violent storm	28.5 - 32.6	Many damages, difficult to walk
Hurricane	32.7 -	Serious damages

Table 2.5. Wind force (Beaufort) and wind velocity (m/s), from [8].

Temperature, all Denmark [°C]												
	J	F	M	A	M	J	J	A	S	O	N	D
Extreme maximum (1874-1994)	12.0	15.8	22.2	28.6	32.8	35.5	35.3	36.4	32.3	24.1	18.5	14.5
Average monthly maximum (normal 1931-1960)	6.8	6.7	10.7	16.5	23.6	26.0	26.9	24.8	21.5	16.4	10.9	8.2
Average daily mean maximum (1961-1990)	2.0	2.2	4.9	9.6	15.0	18.7	19.8	20.0	16.4	12.1	7.0	3.7
Mean (1961-1990)	0.0	0.0	2.1	5.7	10.8	14.3	15.6	15.7	12.7	9.1	4.7	1.6
Average daily mean minimum (1961-1990)	-2.9	-2.8	-0.8	2.1	6.5	9.9	11.5	11.3	9.1	6.1	2.3	-0.7
Average monthly minimum (normal 1931-1960)	-9.9	-10.0	-7.2	-3.0	0.5	4.5	7.3	7.0	2.9	-1.4	-5.2	-8.3
Extreme minimum (1874-1994)	-31.2	-29.0	-27.0	-19.0	-8.0	-3.5	-0.9	-2.0	-5.6	-11.9	-21.3	-25.6
Relative humidity, all Denmark [%]												
Dayly average (1961-1990)	91	90	87	80	75	77	79	79	83	87	89	90
At 8 a.m.	91	90	89	84	77	77	81	85	89	91	92	91
At 2 p.m.	88	83	77	69	62	64	66	68	72	77	86	89
At 9 p.m.	91	90	89	86	81	83	85	89	90	91	91	92
Wind velocity [m/s]												
Inland stations (1982-1995)	5	6	6	5	4	4	5	4	4	5	5	4
Coast stations (1961-1990)	7	7	7	6	6	6	6	6	7	7	8	8
No. of windy days ($v \geq$ 10,8 - 13,8 m/s)	5.0	3.9	4.6	4.0	3.0	2.6	2.2	2.5	2.8	3.4	4.2	4.3

Table 2.6. Typical weather data in Denmark. Based on data from Denmarks Meteorological Institute. See note 2.1.

Note 2.1: Explanation of names used in table 2.6.

Average monthly temperatures refering to All Denmark are measured at a number of weather stations, well distributed in Denmark, typically 30. The averages are calculated on the basis of the periods mentioned in parenthesis.

Mean temperatures:

Mean values of temperatures measured each 6 hours.

Average daily mean maximum/minimum:

Mean of 30 weather stations

Average monthly maximum/minimum:

Mean of 30 weather stations

Extreme maximum/minimum:

Maximum/minimum value measured at any weather station.

3. Methods

When a contractor plans a casting process he selects one or more curing methods sufficient to meet the requirements of the project material. This selection is part of an optimization process where the structure itself and various production methods are related to economical and technical considerations.

The main purposes of the curing methods are:

- to control the evaporation of water
- to control the concrete temperature.

Some normally used curing methods include:

- covering the concrete with nonpermeable membranes
- keeping the concrete in the mould
- adding curing compounds
- keeping the surface wet
- controlling the climate

Finally, adding various components to the concrete is a possible method.

In this chapter the various curing methods are described including their advantages and drawbacks as well as problems concerning planning and documentation.

Appendix 2 gives an overview of the curing methods.

3.1 Non-permeable membranes

Nonpermeable membranes are plastic films, tarpaulins, mineral wool mats and plastic foam mats.

3.1.1 Plastic film

Plastic films must be in close contact with the concrete surface to be as efficient as possible to prevent evaporation. They are best suited to be used on horizontal surfaces and less well suited on vertical, stripped surfaces and on the under sides of concrete structures.

If the fresh concrete is covered by plastic film very soon after casting, before setting time, it involves a risk of leaving marks in the concrete. When the concrete has hardened it is left with a stained or shiny look, caused by condensation under the plastic film. When these kind of stains are not acceptable, they can be partly prevented by placing a layer of felt between the concrete and the plastic film. However, this makes the curing process more complicated and expensive. Moreover, the felt will be damaged by placing it on fresh concrete because it sticks to the concrete.

The plastic film to be used must be unbroken and it must be placed with sufficient overlays. In order to prevent it from being moved by the wind it is normally necessary to keep it down to the surface by means of wooden boards or wet sand. The efficiency of the plastic film must be controlled regularly during the hardening process.

Handling the plastic film is difficult in moderate to strong wind. Plastic film is easily damaged and so its durability and reuse is very low.

3.1.2 Tarpaulin

Tarpaulins must be placed close to the concrete surface in order to prevent evaporation in an efficient manner. This method is well suited on horizontal surfaces as well as on demoulded, vertical surfaces.

If the fresh concrete is covered by tarpaulin very soon after casting, before setting time, it involves a risk of leaving marks in the concrete. When the concrete has hardened it is left with a stained or shiny look caused by condensation under the tarpaulin. When this kind of stains are not acceptable, they can be partly prevented by placing a layer of felt between the concrete and the tarpaulin. However, this makes the curing process more complicated and expensive. Moreover, the felt will be damaged by placing it on fresh concrete because it sticks to the concrete.

Tarpaulins are efficient in use on vertical, demoulded surfaces to prevent evaporation. Usually a tarpaulin is long enough to cover a vertical surface, cast in one operation. The weight of the tarpaulin itself is usually sufficient to keep it in close contact with the concrete surface. The tarpaulin must be fastened at corners, at overlays and at the bottom of the structure.

Tarpaulins are easy to handle, they have a good durability and reuse.

A tarpaulin must be unbroken and it must be placed with sufficient overlays. In order to prevent it from being moved by the wind it is normally necessary to keep it down to the surface by means of wooden boards or wet sand. The efficiency of the plastic film must be controlled regularly during the hardening process.

3.1.3 Mineral wool mats

The main purpose of using mineral wool mats is to control the temperature during the hardening process, but as they are normally covered by plastic films, they prevent evaporation as well.

Mineral wool mats must be placed in close contact with the concrete surface in order to prevent the evaporation efficiently, and proper overlays between the mats must be ensured. The mats are well suited on horizontal surfaces. Mineral wool mats are not suited for use on vertical surfaces.

If the fresh concrete is covered by mineral wool mats very soon after casting, before setting time, it involves a risk of leaving marks in the concrete. When the concrete has hardened it is left with a stained or shiny look, caused by condensation under the matt. When this kind of stains are not acceptable, they can partly be prevented by placing a layer of felt between the concrete and the mat. However, this makes the curing process more complicated and expensive. Moreover, the felt will be damaged by placing it on fresh concrete because it sticks to the concrete.

Mineral wool mats are not very efficient in use on vertical, demoulded surfaces to prevent evaporation. Usually the mats are long enough to cover a vertical surface, cast in one operation, and if the mats are fastened at the bottom, a good contact with the concrete surface can be obtained. However, as the width of the mats is small, many overlays are required, introducing an increased risk of wind tunneling behind the mats whereby the efficiency of the mats is reduced.

Mineral wool mats are easy to handle, but the plastic film on their surfaces is vulnerable. Nevertheless, the mats are considered to be very durable and reusable.

A mineral wool mat to be used must be unbroken and it must be placed with sufficient overlays. In order to prevent it from being moved by the wind it is normally necessary to keep it down to the surface by means of wooden boards. The efficiency of the mats must be controlled regularly during the hardening process.

3.1.4 Mats of polystyrene foam

The main aim of using polystyrene foram mats is to control the temperature during the hardening process, but as they have a dense structure they also prevent evaporation from the surface.

Mats of polystyrene foam are delivered in wide rolls, and the material is more stiff than mats of mineral wool. The mats must be placed close to the surface in order to prevent evaporation. Mats of polystyrene are well suited for horizontal surfaces. They can also be used on vertical surfaces by binding the mats to columns.

The weight of the mats is very low and as they are rather stiff it can be difficult to place them on fresh concrete surfaces without leaving marks in the concrete. When the concrete has hardened it is left with a stained or shiny look, caused by condensation under the matt. When this kind of stains are not acceptable, they can partly be prevented by placing a layer of felt between the concrete and the matt. However, this makes the curing process more complicated and expensive.

As the mats are rather wide the number of overlays becomes small. The overlays must be kept close together to prevent wind tunnels. The efficiency of the cover must be inspected regularly during the hardening process.

Mats of polystyrene foam are not very efficient on vertical surfaces, as it is normally difficult to keep them close to the surface. Yet, at columns and short walls the mats can be tied to the structure to give an effecient protection against evaporation.

Mats of polystyrene foam are easy to handle on horizontal surfaces, but because of their low weight they have to be kept to the surface by other means. The mats are robust and very durable and reusable.

3.2 Moulds

The mould protects the concrete from evaporation, but the efficiency of the mould depends on the surface structure of the mould as well as on the general quality of the mould system.

The surfaces of a mould are normally made of varnished wood/plywood, timber boards or steel. In special cases a form liner of fibre material is prescribed in order to obtain an improved quality of a concrete surface, when cast against a mould.

Using the mould as the only protection from evaporation is an expensive and delaying solution in the building process, because the opportumity of reusing the mould is reduced.

Whenever the requirement on the curing is a long curing period, it will normally be met by some combination of a period in mould followed by a final period with a different kind of protection after demoulding.

Situations where additional evaporation protection is required after demoulding are covered by the methods described in this chapter. It is important that continued curing is established shortly after demoulding in an effcient way, so that requirements described in chapter 2 are met.

When a short curing period is required the concrete is normally kept in the mould until the requirement is met.

3.2.1 Varnished wood/plywood or steel

Moulds of varnished wood/plywood of steel give an improved protection against evaporation because the surfaces are water tight and non-sucking.

3.2.2 Timber formwork

Timber formwork protects the concrete from evaporation, but if the wood is dry it will suck some water form the concrete. So it is important to ensure that timber formwork is tight and non sucking by wetting it.

3.2.3 Form liner

Moulds with form liner do not protect better from evaporation than other types of tight moulds. The aim of using form liner is to obtain a smooth surface without air bubbles which is similar to the surface obtained when using timber formwork.

The use of form liner is an extra cost, so it is only used when necessary. The form liner must be mounted very carefully in order to ensure that it is kept close to the mould without folding. Form liner is normally not reuseable.

3.3 Curing compounds

The main purpose of using curing compounds is protect fresh concrete surfaces from evaporation. It is typically used at horizontal surfaces where special problems with other types of curing exist.

Curing compound is a liquid with a dissolved emulsion of organic components that produce a nevaporation retarding film on the concrete surface. An example can be water with an emulsion of wax which produces a film of wax. Another example is an organic solvent such as alcohol, terpentine or xylene in which resin, acrylat or the like is dissolved and produces an evaporation retarding film.

Curing compounds must reduce the evaporation by 75%, see chapter 2.3.

Curing compounds must be applied in the quantities specified by the producer. Most products contain a colour pigment as an aid to control the dosing by visualising the dosed amount. In windy weather it may be difficulty to produce a proper curing with curing compounds. Another problem is vertical surfaces where it is normally necessary to apply the curing compound several times in order to obtain the prescribed thickness of the layer.

Curing compounds may influence the result of a subsequent surface treatment by reducing the adhesion property of the surface. Normally it is not allowed to use curing compounds on surfaces that shall later be sealed by membranes. The effect of the curing membrane normally decreases with time, a fact that must be included in the considerations when a curing method is selected. Curing compounds are normally not allowed to be used in construction joints or protruding bars of reinforcement. If accidentally used it must be removed by sand blasting.

3.4 Wetting

A concrete surface can be kept wet by sprinkling water to it, by adding a film of water or by placing wet hessian sacks on the surface. These methods are mainly used to protect surfaces of hardened concrete (1-2 maturity days). They are not allowed on fresh concrete because a surplus of water might wash out the concrete surface. Wetting is mainly used on horizontal surfaces to supplement other methods and it must not be used in such a manner that the temperature of the concrete is changed drastically, see [9].

Using wetting as a curing method requires continuous inspection of the efficiency in order to prevent periods with drying out. A strong wind can also reduce the efficiency, and wetting must not be used when frost can be expected.

Water films and sprinkling may cause problems to other working processes going on, especially if such wetting methods are used at high levels of the structure. In construction joints it is often better to use wetting methods than curing compound. Wetting methods imply risks of stains and miscolouring of the surface.

3.5 Climate control

Climate control is a method, where the temperature and relative humidity of the air is controlled in order to reduce evaporation from or condensation to the concrete surface.

Whenever the vapour pressure of the air is higher than that of the concrete surface, the wind velocity does not influence the evaporation rate. When evaporation takes place, i.e. the vapour pressure of the air is lower than that of the concrete surface, the evaporation rate is increased by the wind velocity.

Similar effects can arise naturally outdoors, when the air temperature is higher than that of the concrete and at the same time the relative humidity is high. Such situations may be found especially in the springtime or the autumn and the result is a reduced evaporation or even a condensation on the concrete surface, when the vapour pressure of the air is higher than that of the concrete surface.

Climate control is used in industrial production of concrete elements and concrete products, but it can also be used on site, for instance when casting concrete structures under a tent.

3.6 Additives

Polymers:

Addition of polymers to a concrete mixture may produce a sealing effect internally in the concrete so that the water evaporation from the surface is reduced. In order to be of some effect big quantities of polymer are required, so the method is normally not economical when used in normal concrete production.

It may seem tempting to add polymers to reduce the evaporation, but the method is not economical and only little is known about the effects of polymers on the consistency and pore structure of the concrete, so the method should not be used.

Addition of fibres:

Addition of very short plastic fibres is increasingly used in large, horizontal structures. The amount of fibres added is small and does not reduce the evaporation, but cracks caused by plastic shrinkage are distributed more evenly because of the elasticity of the plastic fibres so that the cracks may become invisible to the naked eye.

Of course it is necessary to cure the concrete when fibres are added, but the addition of fibres may offer an increased guarantee against visible plastic shrinkage cracks if the curing fails for some reason. The type and amount of fibres must be evaluated individually.

When addition of plastic fibres is prescribed, most concrete producers make reservations especially as to the pore structure of the concrete. Such reservations must be considered, when the method is prescribed.

4. Planning and Inspection

Planning of the curing is a way to ensure that all requirements on the concrete during the hardening period are met. The planning can be supported by computer simulations of the hardening process.

Inspection is necessary to ensure that the requirements have been met during the hardening period after the casting.

Two types of requirements are made (for further requirements, see note 4.1):

1. The starting time of the curing
2. The length of the curing period

Note 4.1: Examples of further requirements in the project:

- The concrete must be frost resistant before it is submitted to frost
- Maximum allowed temperature differences in concrete sections
- Maximum allowed temperature differences at construction joints
- Maximum allowed tensile stress related to the tensile split test strength
- Minimum strength at demoulding

Computer simulations can be used for planning the curing so that these additional requirements can also be met. These subjects are discussed in [8] and [9].

Appendix 3 is a collection of forms that can be used for planning the curing. When these forms are used, it is ensured that sufficient information are available for calculations to demonstrate that the requirements will be met.

Forms for use in planning:

Planning 1: Concrete

Required information about the concrete mixture, environmental class and adiabatic heat development.

Planning 2: Time to start the curing

Definition of maximum time before curing is started

Planning 3: Minimum period of curing

Calculation of required period of curing

Planning 4: Temperature and maturity

Information necessary to carry out computer calculations of the concrete temperature and the hardening process.

Further in appendix 3 forms for inspection are found, see below.

Forms for inspection are:

Inspection 1: Curing schedule

A form for describing the planned curings.

Inspection 2: Record of curing

A form for recording the curing activities as they are performed and for comparison with the schedule.

Inspection 3: Calculation of maturity

A form for calculation of the maturity from temperature measurements performed during the curing period.

4.1 Planning

During the planning process a number of decisions must be taken regarding the concrete, curing methods and climate conditions.

4.1.1 The concrete

The requirements on curing depend on the selection of type of concrete. If different concretes are able to meet the requirements of the project, a calculation of the hardening process of each concrete should be performed.

For calculation of temperature and maturity knowledge of the binder content and adiabatic heat development is necessary, so the adiabatic heat development is measured during the pre-test.

The heat development in the concrete generates a temperature rise in the concrete, so that the surface temperature of the concrete normally is equal to or a few degrees higher than the air temperature.

An estimate of the concrete temperature at casting can be given by the concrete producer. It can also be calculated as described in [8]. As an alternative the procedure below can be used:

4.1.2 Curing methods

Curing methods are evaluated and selected on the basis of economical and technical considerations, as mentioned in chapter 3.

4.1.3 Climate

For short term forecasting of the air temperature and wind velocity the weather reports from a local weather station should be used. If such data are not available (longer term forecasts), the data in table 2.6 can be used to predict the air temperature, relative humidity and wind velocity.

Both average and extreme weather situations should be calculated, as variations in the weather can be of great influence on the curing.

At indoor castings in a closed room a typical wind velocity of 2 m/s can be used in the calculations.

4.1.4 Surface heat transmission coefficient

The heat transmission coefficient of a concrete surface is required to calculate of the temperature and maturity development. The heat transmission coefficient expresses the thermal insulation of the curing.

The heat transmission coefficient k can be calculated by formula (4.1).

$$k = \frac{1}{\left(\frac{1}{\alpha_k} + \left(\frac{e}{\lambda}\right)_{insul(1)} + \left(\frac{e}{\lambda}\right)_{insul(2)} + \ldots + \left(\frac{e}{\lambda}\right)_{insul(N)} + \left(\frac{e}{\lambda}\right)_{mould}\right)} \qquad (4.1)$$

The coefficient of heat transmission by forced convection α_k is calculated by formula (4.2), see [8]:

$$\alpha_k \cong 20 + 14 \cdot v \quad [kJ/m^2 \cdot h \cdot °C] \quad \text{for } v \leq 5 \text{ m/s}$$
$$\alpha_k \cong 25.6 \cdot v^{0.78} \quad [kJ/m^2 \cdot h \cdot °C] \quad \text{for } v > 5 \text{ m/s} \qquad (4.2)$$

where:

e	=	Thickness of insulating layer [m]
insul(N)	=	Number of insulating layers
k	=	Heat transmission coefficient [$kJ/m^2 \cdot h \cdot °C$]
v	=	Wind velocity [m/s]
α_k	=	Surface heat transmission cofficient by convection [$kJ/m^2 \cdot h \cdot °C$]
λ	=	Thermal conductivity [$kJ/m \cdot h \cdot °C$].

Figure 4.1 shows heat transmission coefficients as a function of wind velocity for a number of moulds and insulation materials.

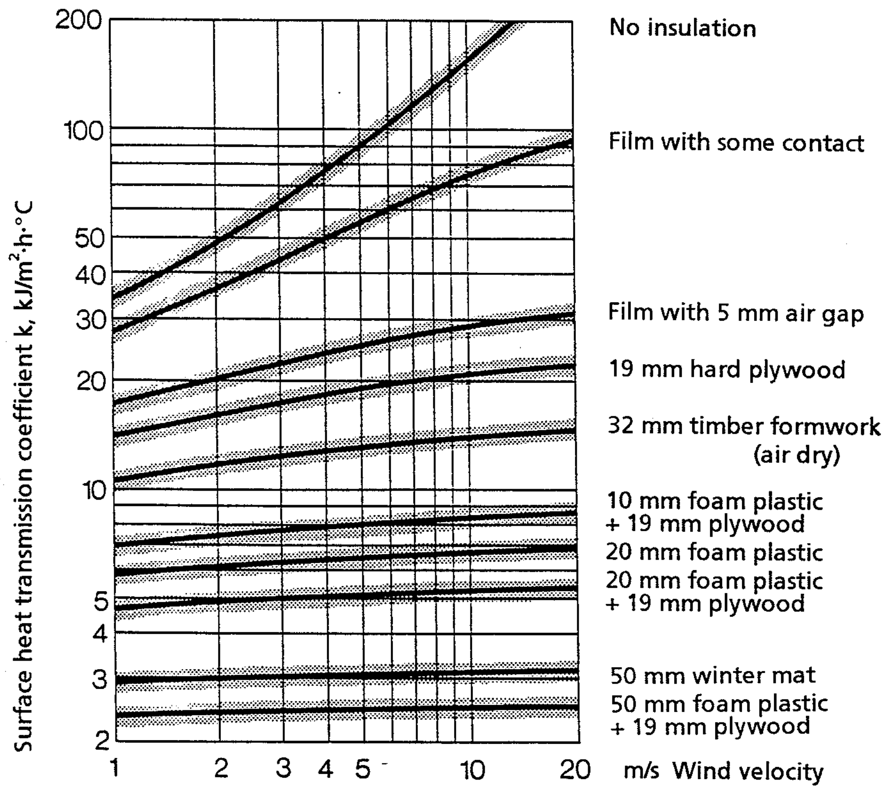


Figure 4.1. Heat transmission coefficient k as a function of wind velocity v for typical moulds and insulating materials. Ref. [8].

4.2 Inspection

Inspection must be performed during the curing period in order to ensure that the stipulated requirements are met. It must also be documented, that the starting time and the time period of the curing are fulfilled.

4.2.1 Starting time

If table 2.1 or 2.2 are used for outdoor casting, the concrete temperature must be measured from the time of casting until the curing is started. The temperature must be measured in the concrete at a depth of maximum 10 mm below the surface. Temperature measurements are described in [9].

The average of the measured temperatures is used in table 2.2. If the curing is started before the end of the relevant time periods mentioned in table 2.2, then the requirements on the starting time are met, and no further calculation is needed.

If on the other hand table 2.1 is used, the evaporated amount of water before start of curing must be calculated by formula (4.3). The calculation must show values lower than those mentioned in table 2.1.

$$\text{Evaporated water} = \dot{w} \cdot \Delta t \quad [\mathrm{kg/m^2}] \tag{4.3}$$

Δt is the time (hours) elapsed before the curing is started.
$\dot{w}$ is the rate of evaporation, calculated as described in example 2.4.

In the calculation is used the average of concrete and air temperatures measured from casting until start of curing. The relative humidity can be taken from table 2.6 with sufficient accuracy. The wind velocity must be measured or reported by a local weather station.

The maturity of the concrete at the time of starting the curing must be documented by means of temperature measurements. It must be verified that this maturity is less than or equal to the setting time τ_0 plus 1 hour.

4.2.2 Curing period

The duration of the curing is always expressed in terms of maturity of the concrete surface. The temperature to document the maturity must be measured in the concrete surface in a depth of maximum 10 mm below the surface.

When temperature measurements and calculation of maturity are performed by the same equipment, no further documentation is required on the maturity of the concrete surface.

If temperature measurements are performed without simultaneous calculation of the maturity, the maturity must be calculated for the total hardening period of the concrete.

The calculation of maturity is described in example 4.1 below.

Example 4.1. Calculation of maturity

The maturity of a concrete is assumed to be calculated on the basis of temperature measurements in the concrete 5 mm below the surface. Table 4.1 shows a filled in version of the form Inspection 3: Calculation of maturity.

The surface temperature $\theta_{concrete}$ has been measured at times h [hours] after casting, see the two first columns in table 4.1. The third column shows the time difference Δt between two temperature measurements. In the fourth column the averages of consecutive temperature measurments $\overline{\theta}_{concrete}$ are calculated.

H is the velocity factor which can be taken from appendix 4. H is evaluated from the average temperature $\overline{\theta}_{beton}$. The increase in maturity ΔM in the sixth column is calculated by $H \cdot \Delta t$. The maturity M of the concrete in the last column is calculated by adding the values of ΔM one by one from the top.

In table 4.1 can be seen that the concrete has reached M = 3.2 maturity hours after h = 6 (normal) hours. After 28 (normal) hours the maturity of the concrete is 21 maturity hours.

The curing must be continued until the concrete has obtained the relevant maturity M as mentioned in chapter 2.2.

h [hours]	$\theta_{concrete}$ [°C]	Δt [hours]	$\overline{\theta}_{concrete}$ [°C]	H	ΔM [hours]	M [hours]
0	10					0
		6	11.0	0.54	3.2	
6	12					3.2
		3	12.5	0.62	1.9	
9	13					5.1
		3	13.5	0.67	2.0	
12	14					7.1
		3	14.5	0.72	2.2	
15	15					9.3
		4	15.5	0.77	3.1	
19	16					12.4
		2	16.5	0.83	1.7	
21	17					14.1
		4	18	0.90	3.6	
25	19					17.7
		1	20	1.00	1.0	
26	21					18.7
		2	23	1.15	2.3	
28	25					21.0

Table 4.1. Calculation of maturity on the basis of temperature measurements. The velocity factor H can be found in appendix 4.

5. Examples of Planning

This chapter presents two examples of planning the curing process. The first example presents calculations on a concrete floor. The second example presents curing of a wall.

5.1 Concrete floor cast during August

Suppose a concrete floor is to be cast during the month of August. Various types of concrete are investigated during the planning, and various weather conditions are assumed.

5.1.1 The concrete

In the project material is prescribed aggressive environmental class (A).

Three types of concrete are investigated: A, B and C. Each of them meet the requirements of the project. Table 5.1 has been filled in on the basis of the BBB-forms corresponding to the three types of concrete with their content of micro silica MS og fly ash FA.

For each combination of FA and MS has been read in table 2.1 the maximum allowed amount of evaporated water before curing must be started, see the last column in table 5.1.

Type of concrete	FA + MS, weight-% of binder content	MS, weight-% of binder content	Maximum evaporated amount of water kg/m^2
A	20.2	3.4	1.5
B	10	0	3.0
C	0	0	6.0

Table 5.1. Content of FA and MS in the concretes A, B and C. Requirements on maximum evaporated amount of water before curing must be started are taken from table 2.1.

The adiabatic heat development of the concretes has been measured and given in the BBB form, see table 5.2.

Type of concrete	Binder content $[kg/m^3]$	Q_∞, [kJ/kg binder]	τ_e, [hours]	α
A	357	280	14.2	0.96
B	341	267	15.8	1.01
C	400	388	9.9	0.88

Table 5.2. The heat development of concretes A, B and C. Q_∞, τ_e and α have been evaluated by measurements. The binder content = C + FA + MS has been taken from the BBB-forms of the concretes.

As an example the data of concrete type A are shown in form B5.1.1 in appendix 5.1.

The concrete producer states that the concrete temperature during August will be typically 20°C.

5.1.2 Climate

In this example the following 5 climate conditions are planned :

Situation 1 (typical August climate):
The floor is to be cast during August and typical climate data are read from table 2.6. The mean temperature of a day in August is 15.7°C. The construction site is Odense which is an inland station, so the wind velocity is 4 m/s.The floor is intended to be cast at 8 a.m. in the morning when the relative humidity is 85%. These data to be used in the calculation are shown in form B5.2

Concrete temperature	= 20°C
Air temperature	= 15.7°C
Relative humidity	= 85%
Wind velocity	= 4 m/s

Situation 2:
This situation presupposes that the casting will be delayed until noon. From table 2.6 is found that the relative humidity has changed into 68% at 2 p.m. The temperatures and wind velocity are assumed to be the same as in situation 1.

Concrete temperature	= 20°C
Air temperature	= 15.7°C
Relative humidity	= 68%
Wind velocity	= 4 m/s

Situation 3:
This situation presupposes that the wind rises into near gale. From table 2.5 is found that this corresponds to a wind velocity of around 15 m/s. This situation is interesting because it is very difficult to predict the wind velocity. The other data are assumed the same as in situation 1.

Concrete temperature	= 20°C
Air temperature	= 15.7°C
Relative humidity	= 85%
Wind velocity	= 15 m/s

Situation 4:
This situation combines situation 2 and 3 with casting at 2 p.m. and high wind velocity. The temperatures are the same as the temperatures in situation 1.

Concrete temperature	= 20°C
Air temperature	= 15.7°C
Relative humidity	= 68%
Wind velocity	= 15 m/s

Situation 5:
This situation presupposes that the air temperature is lower than the mean temperature. An air temperature of 10°C is assumed. The other data are assumed to be the same as in situation 1.

Concrete temperature	= 20°C
Air temperature	= 10°C
Relative humidity	= 85%
Wind velocity	= 4 m/s

5.1.3 Starting time of curing

The procedure to define the starting time is described in the following three examples.

The following three examples present different methods to evaluate the starting time of curing. As an example concrete type A and the typical weather in August is treated (situation 1, see section 5.1.2).

In table 5.3 are shown the calculated times to start the curing of the three concrete types - A, B og C at each of the weather situations in August.

Example 5.1: Reading the starting time of curing in a graph. Table 5.1 shows that only 1.5 kg/m² of water is allowed to evaporate from concrete type A before curing has to be started. In appendix 1 has been selected a graph that covers the assumed climate conditions. The graph with the range of data below is found to cover situation 1:

Concrete temperature = 20°C
Air temperature ≥ 15°C
80% ≤ RH < 90%.

On the line marked wind velocity = 4 m/s it can be read that an amount of water of 1.5 kg/m² has evaporated in 3.3 hours = 3 hours and 20 minutes.

The conclusion is that the curing must be started not later that 3 hours and 20 minutes after casting under the weather conditions of situation 1 when climate conditions covered by situation 1 exist.

Example 5.2: Calculation of the starting time of curing. In the nomogram in figure 2.2 can be found the water vapour presssure P in the air and concrete, corresponding to situation 1:

$P_{concrete}$ (20°C) =	2.4 kPa	(RH = 100%)
P_{air} (15.7°C) =	1.5 kPa	(RH = 85%)

The vapour pressure difference is $\Delta P = P_{concrete} - P_{air} = 0.9$ kPa.
The rate of evaporation $\dot{w}$ can be read or calculated (from v = 4 m/s, see the bottom part of figure 2.2) to be 0.40 kg/m²h.

The period from casting to the point when 1,5 kg/m² have evaporated, can be calculated by the formula (2.5):

$$\text{Time} = \frac{1.5 \text{ kg/m}^2}{0.40 \text{ kg/m}^2\cdot\text{h}} = 3{,}8 \text{ hours} \qquad (5.1)$$

This means that the curing has to be started not later than 3.8 hours after casting when climate situation 1 is assumed.

The two examples 5.1 and 5.2 show slightly different results. This is because each of the nomograms covers a range of values of air temperatures and relative humidities, while the exact values are used in a calculation.

The results from examples 5.1 and 5.2 are transferred into form B5.1.2 in appendix 5.1.

Example 5.3: Reading the starting time of curing in table 2.2. In table 2.2 the latest possible starting time of curing is found to be 1 hour (FA+MS < 35%, MS < 10%, outdoor casting). The resulting value of 1 hour is transferred into form 5.1.2 in appendix 5.1.

However, a calculated result is considered to be more exact than results read from appendix 1 or table 2.2 so a calculation with the result 3.8 hours will overrule the value 1 hour read from table 2.2 and the value 3.3 hours read from appendix 1.

In form B5.1.2 is indicated that the thickness of the concrete is greater than 0.2 m, so the calculated time 3.8 hours shall not be adjusted accordingly.

Table 5.4 shows the starting times of curing of concrete types A, B and C at the five investigated climatic conditions during August. These results have been shown without paranthesis in table 5.4.

These results are based on the assumption that the relative humidity of the concrete surface is 100%. As this is only valid during the early period of hardening (examples 2.4 and 5.2) the following investigation is carried out.

As described in section 2.1 curing must be started 1 maturity hour after setting time τ_0. Then it must be verified whether the requirement has been met. Table 5.3 shows the testing time τ_0 and the related maturity at the starting time of curing.

<table>
<tr><th rowspan="2">Situation</th><th rowspan="2">Climate condition</th><th colspan="3">Starting time of curing [hours]</th></tr>
<tr><th>Concrete A</th><th>Concrete B</th><th>Concrete C</th></tr>
<tr><td rowspan="2">1 (typical August climate)</td><td>$\theta_{concrete}$ = 20°C
θ_{air} = 15.7°C
RH = 85 %
v = 4 m/s</td><td rowspan="2">3.8
(6.8)</td><td rowspan="2">7.5
(5.5)</td><td rowspan="2">15.0
(6.1)</td></tr>
<tr><td>ΔP = 0.9 kPa
$\dot{w}$ = 0.40 kg/m² · h</td></tr>
<tr><td rowspan="2">2</td><td>$\theta_{concrete}$ = 20°C
θ_{air} = 15.7°C
RH = 68 %
v = 4 m/s</td><td rowspan="2">2.8
(6.8)</td><td rowspan="2">5.7
(5.5)</td><td rowspan="2">11.3
(6.1)</td></tr>
<tr><td>ΔP = 1.2 kPa
$\dot{w}$ = 0.53 kg/m² · h</td></tr>
<tr><td rowspan="2">3</td><td>$\theta_{concrete}$ = 20°C
θ_{air} = 15.7°C
RH = 85 %
v = 15 m/s</td><td rowspan="2">1.3
(7.2)</td><td rowspan="2">2.5
(5.9)</td><td rowspan="2">5.0
(6.4)</td></tr>
<tr><td>ΔP = 0.9 kPa
$\dot{w}$ = 1.20 kg/m² · h</td></tr>
<tr><td rowspan="2">4</td><td>$\theta_{concrete}$ = 20°C
θ_{air} = 15.7°C
RH = 68 %
v = 15 m/s</td><td rowspan="2">0.9
(7.2)</td><td rowspan="2">1.9
(5.9)</td><td rowspan="2">3.8
(6.4)</td></tr>
<tr><td>ΔP = 1.2 kPa
$\dot{w}$ = 1.60 kg/m² · h</td></tr>
<tr><td rowspan="2">5</td><td>$\theta_{concrete}$ = 20°C
θ_{air} = 10°C
RH = 85 %
v = 4 m/s</td><td rowspan="2">2.5
(8.5)</td><td rowspan="2">5.0
(6.5)</td><td rowspan="2">10.0
(6.8)</td></tr>
<tr><td>ΔP = 1.40 kPa
$\dot{w}$ = 0.60 kg/m² · h</td></tr>
<tr><td>From table 2.2</td><td></td><td>1.0</td><td>2.0</td><td>4.0</td></tr>
</table>

Table 5.4. Calculated starting times of curing of concrete types A, B og C in 5 different climatic conditions but only one concrete temperature, 20°C.

5.1.4 Curing period

If the contractor selects to cure with curing compound not later than 3.8 hours after casting under typical August climate conditions (situation 1), then the form Planning 3 shall not be used, because the requirement on the curing period will be met in this case.

However, curing with plastic film is selected, and the form Planning 3 (form B5.1.3) has been filled in (only concrete type A).

Because the concrete types A, B and C all satisfy the requirements for an aggressive environment, they have to be cured until the degree of reaction is 85%, see table 2.3. The formula (2.3) can be used to calculate the maturity necessary to reach R = 85% for each of the concrete types. In form B5.1.3 can be seen, as an example, that concrete type A reaches this degree of reaction at 94 maturity hours.

The calculation is based on parameters describing the adiabatic heat development (which can be taken from the concrete form).

If this calculation is not carried out, the concrete type A must, as an example, be cured for minimum 120 maturity hours, see table 2.4. This is caused by the w/c ratio of the concrete and the selection of the environmental class aggressive.

The total result, seen in form B5.1.3, is that concrete type A must be cured for 94 maturity hours.

In a rough estimate the period of time, necessary for the concrete surface to reach a given maturity, can be evaluated. This method is mentioned in the following example 5.4.

Example 5.4. Reaching a given maturity - Rough estimate. The concrete is assumed to reach temperature equilibrium at 15°C with the air within a rather short period, because it is rather thin and not insulated.

If the concrete temperature is assumed to be constant 15°C, it can be calculated by formula (5.2) that the plastic film has to cover the concrete until 125 hours.

$$\text{Time} = \frac{\text{Required time period of curing}}{\text{Velocity factor}} = \frac{94 \text{ hours}}{0.75} = 125 \text{ hours} \quad (5.2)$$

The value 0.75 is the velocity factor H at 15°C, read from the figure in appendix 4.

5.1.5 Computer calculation of temperature and maturity

If a more precise estimate of the curing period is required than that obtained in example 5.4, a computer simulation of the hardening process has to be performed.

In the calculation it is assumed that the concrete is covered with plastic film at the times given in table 5.3. Table 5.4 shows the periods of curing necessary to reach a degree of reaction of R = 85% so that the plastic film can be removed. Climate data are taken from section 5.1.2, and heat transmission coefficient k are taken from section 4.1.4.

In form B5.1.4 in appendix 5 is as an example shown concrete type A and climate conditions situation 1. The heat transmission coefficients in form B5.1.4 have been read in figure 4.1 at a wind velocity of v = 4 m/s, corresponding to a free concrete surface and a surface covered with plastic film, respectively.

Situation	Climatic conditions	Curing period with platic film, hours		
		Concrete A	Concrete B	Concrete C
1 and 2	$\theta_{concrete}$ = 20°C θ_{air} = 15.7°C v = 4 m/s Transmission coefficients: k(free surface) = 75 kJ/m²·h·°C k(plastic film) = 50 kJ/m²·h·°C	104	112	87
3 and 4	$\theta_{concrete}$ = 20°C θ_{air} = 15.7°C v = 15 m/s Transmission coefficients: k(free surface) = 200kJ/m²·h·°C k(plastic film) = 85 kJ/m²·h·°C	110	114	99
5	$\theta_{concrete}$ = 20°C θ_{air} = 10°C v = 4 m/s Transmission coefficients: k(free surface) = 75 kJ/m²·h·°C k(plastic film) = 50 kJ/m²·h·°C	144	151	124

Table 5.4. Calculated period of curing with platic film corresponding to a degree of reaction of 85 % in the concrete surface. The curing has been started at times as described in table 5.3.

With this information the form Inspection 1 can be filled in for each type of concrete and climate situation. The actual form given to the foreman shall correspond to the concrete specification and the climate condition at the time of casting. In form B5.1.5 a form for inspection has been filled in corresponding to the concrete type A at typical climate conditions during August (situation 1).

5.2 Concrete wall cast during October

In this example the curing of a concrete wall, 700 mm thick, is planned.

5.2.1 General requirements

In the project material is prescribed aggressive environmental class (A).

5.2.2 The concrete

Three types of concrete are investigted: A, B and C, as described in the previous section 5.1.1. Calculations of the hardening process are performed for these concretes. As an example the data for concrete type B is shown in form B5.2.1 in appendix 5.2.

The concrete is planned to be cast in a mould. Therefore requirements on the start of curing do not have to be documented. Immediately after casting the top of the mould is covered with plastic film, fixed to the mould. This is entered in the form B5.2.4 for concrete B.

The concrete producer has given the following information: The concrete temperature follows the air temperature and the concrete termperature will be a few degrees higher than the air temperature during October.

5.2.3 Curing period

The curing period has been estimated from section 2.2. In tables 2.3 and 2.4 it has been read for each of the used concretes that a mimimum degree of reaction of 85% must be reached, corresponding to 120 maturity hours. The information has been entered in form B5.2.2 for concrete type B.

It is seen that concrete type B reaches 85% of degree of reaction after 95 maturity hours and so must be cured during minimum 95 maturity hours. Concrete type C reaches R = 85% at 78 maturity hours. Concrete type A reaches R = 85% at 94 maturity hours.

All three concretes are cured until 85% degree of reaction has been reached, as this is the most gentle demand.

5.2.4 Curing methods

The contractor is going to use 5/4" timber boards (thickness 32 mm) in order to obtain a specified surface structure.

The timber formwork must be reused as quick as possible, corresponding to demoulding on the day after casting (18 hours after casting). It is allowed to use curing compound or tarpaulins for curing after demoulding.

5.2.5 Climate and heat transmission coefficients

During the state of planning three climate situations in October are investigated.

Situation 1:

Concrete temperature	= 15°C
Air temperature	= 9.1°C
Wind velocity	= 5 m/s

Typical data for October taken from table 2.6.
The wall shall be cast in Roskilde (land station) corresponding to v = 5 m/s.

Situation 2:

Concrete temperature	= 20°C
Air temperature	= 16°C
Wind velocity	= 5 m/s

Rather high temperature and a typical wind velocity, see table 2.6.
This produces a rather quick development of maturity in the surface layer of the concrete.
The air temperature have been provided by the weather forecast station (gentle breeze, see table 2.5).

Situation 3:

Concrete temperature	= 20°C
Air temperature	= 16°C
Wind velocity	= 10 m/s

Like situation 2, but with higher wind velocity, as the wind velocity is normally very difficult to predict during the hardening period (Fresh breeze, see table 2.5).

Figure 4.1 is used to read the following heat transmission coefficients k:

With v = 5 m/s:

32 mm timber formwork	k = 14 kJ/m² · h · °C
Uncovered surface (including curing compound)	k = 90 kJ/m² · h · °C
Tarpaulin	k = 19 kJ/m² · h · °C

With v = 10 m/s:

32 mm timber formwork	k = 15 kJ/m² · h · °C
Uncovered surface (including curing compound)	k = 150 kJ/m² · h · °C
Tarpaulin	k = 22 kJ/m² · h · °C

5.2.6 Computer calculation of temperature and maturity

Table 5.5 presents the curing periods calculated for the concrete types A, B and C under the three climate conditions mentioned above and with tarpaulin used as curing method. Estimates of k are taken from the previous section.

Calculations of the development of temperature and maturity in the surface are based on data from table B5.2.3 and the adiabatic heat development from table B5.2.1. Typical climate data of October have been taken from section 5.2.5 and shown in form B5.2.3 as an example.

Certain computer programs require values of the concrete density, heat capacity and thermal conductivity to be input as constants (see form B5.2.3), and in other programmes such constants are calculated automatically from the concrete composition.

Situation	Climate and concrete	Minimum curing period (tarpaulin) Concrete A	Concrete B	Concrete C
1	$\theta_{concrete}$ = 15°C θ_{air} = 9.1°C v = 5 m/s	≈72 hours ≈ 3 days	≈84 hours ≈ 3.5 days	≈36 hours ≈ 1.5 day
	k(mould) = 14 kJ/m²·h·°C k(free surf.) = 90 kJ/m²·h·°C k(tarpaulin) = 19 kJ/m²·h·°C			
2	$\theta_{concrete}$ = 20°C θ_{air} = 16.4°C v = 5 m/s	≈53 hours ≈ 2.2 days	≈60 hours ≈ 2.5 days	≈31 hours ≈ 1.3 days
	k(mould) = 14 kJ/m²·h·°C k(free surf.) = 90 kJ/m²·h·°C k(tarpaulin) = 19 kJ/m²·h·°C			
3	$\theta_{concrete}$ = 20°C θ_{air} = 16.4°C v = 10 m/s	≈60 hours ≈ 2.5 days	≈67 hours ≈ 2.8 days	≈36 hours ≈ 1.5 days
	k(mould) = 15 kJ/m²·h·°C k(free surf.) = 150 kJ/m²·h·°C k(tarpaulin) = 22 kJ/m²·h·°C			*)

Table 5.5. Calculated periods of curing with tarpaulin corresponding to a degree of reaction of 85 % in the concrete surface. The wall was demoulded at 18 hours after casting and the curing with tarpaulin was started 1 hour after demoulding.
*) Demoulded at 2 days after casting in order to prevent big temperature differences in the structure, as required in the project.

Definitions

Adiabatic heat development	The heat development in concrete during the hardening process, provided no heat is transferred to the surroundings.
Activity factors	Factors used to calculate the equivalent cement content where the amounts of fly ash and micro silica are included in the cement. Common practice is to use an activity factor of 0.5 for fly ash and an activity factor of 2.0 for micro silica.
Binder content	The total content of cement, fly ash and microsilica in the concrete [kg/m^3].
Curing	Any method used to reduce the loss of water from the concrete surface. Such methods include: Maintaining the mould, covering the concrete with plastic film, tarpaulin, mats of mineral wool or plastic foam, watering the concrete, spraying curing compound on the concrete surface or controlling the climate of the surroundings.
Curing compound	Liquid which is sprayed onto the surface of the concrete in order to protect it from evaporation.
Velocity factor	Factor used for multiplying the time in order to calculate the maturity of a concrete. It is defined as the ratio of the velocity of reaction at a certain temperature to the velocity of reaction at 20 °C.
Hardening process	A term describing the fact that a concrete is plastic at the time of casting and that it gradually develops strength and stiffness by means of chemical reactions between the cement, fly ash, micro silica and water.
Maturity	Time elapsed since casting, provided the temperature of the concrete is 20°C. At other temperatures the time is multiplied by the velocity factor.
Plastic shrinkage	Cracks in the surface of fresh concrete may be caused by plastic shrinkage when the tensile stress becomes bigger than the tensile strength. Plastic shrinkage is influenced by the water loss by evaporation.

Drying of hardening concrete

The concrete dries by a combination of water loss, which is caused by evaporation from the surface, and internal drying, which is caused by the chemical reactions between water and cement.

Water loss from fresh concrete

Water will evaporate from a fresh concrete if the water vapour pressure in the concrete surface is bigger than that in the air. The rate of water loss from a fresh concrete surface is controlled by the wind speed and by the difference in water vapour pressure between the concrete surface and the surrounding air.

Water movements in concrete

During the first few hours of the hardening process the rate of water flow to the surface drops rapidly, because the initially open pore system in the concrete is closed by the hydration products. In the hardened concrete the water flow is reduced to a minimum and only water vapour diffusion takes place.

Symbols

C	Cement content of the concrete [kg/m^3].
e	Thickness of an insulating layer [m]
E	Activating energy [J/mol]. The activating energy describes the influence of the temperature on the velocity of chemical reactions. A high activating energy means that the velocity of chemical reactions is increased much, by a given rise of the temperature.
FA	Fly ash content of the concrete [kg/m^3].
h	Hours.
H	Velocity factor. H describes the velocity of a reaction at a certain temperature divided by the velocity of the same reaction at 20 °C. H is used in the calculation of the maturity M of the concrete.
k	Heat transmission coefficient [$kJ/m^2 \cdot h \cdot °C$].
M	Maturity [hours] or [days]. Time elapsed since casting, provided the temperature of the concrete is 20°C. At other temperatures the time is multiplied by the velocity factor.
MS	Micro silica content of the concrete [kg/m^3].
$P_{concrete}$	Water vapour pressure in the surface of the concrete [kPa].
P_{air}	Water vapour pressure in the air surrounding the concrete [kPa].
Q(M)	Adiabatic heat development as a function of the maturity M [kJ/kg binder].
Q_∞	Calculated value of total heat development at infinitely high maturity. The value is one of three parameters in Freiesleben's model for calculation of Q(M).
$\bar{R}$	The universal gas constant. $\bar{R} \approx 8,314$ J/mol·K.

R	Degree of reaction, hydration or hardening (dimensionless). R describes the ratio of the amount of reacted binder to the inital amount of non reacted binder. In practice, however, R is described by the ratio of adiabatic heat generated at a certain maturity M to the total amount of adiabatic heat generation, i.e. $R = Q(M)/Q_{\infty}$.
RH	Relative humidity of air (dimensionsless). RH is defined as the ratio of the actual water vapour pressure to the water vapour pressure at saturation, or as the ratio of the actual water content to the water content at saturation.
t	Time [hours].
v	Wind velocity [m/s].
$\dot{w}$	Velocity of evaporation of water from a concrete surface. [$kg/m^2 \cdot h$].
w/c_e	Equivalent water/cement ratio. It is defined as the ratio of the water content to the sum of content of cement, fly ash and microsilica, in which the content of fly ash and micro silica multiplied by the activity factors.
α	Curvature parameter which is one of three parameters in Freiesleben's model for calculation of Q(M).
α_c	Surface heat transmission coefficient [$kJ/m^2 \cdot h \cdot °C$].
ΔM	Increase in maturity [hours].
ΔP	Vapour pressure difference between a concrete surface and the surrounding air [kPa].
Δt	Time difference [hours].
λ	Heat conductivity [$kJ/m \cdot h \cdot °C$].
$\theta_{concrete}$	Temperature in the concrete surface [°C].
$\bar{\theta}_{concrete}$	Average temperature in the concrete surface [°C]
θ_{air}	Air temperature [°C].

τ_e	Time constant which is one of three parameters in Freiesleben's model for calculation of Q(M). [hours]

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[1] Berrig, A. & Haugaard M. & Fogh Jensen, P.: "HETEK, Curing, State of the Art", Report No. 37, ISBN 87 7491 6912, ISSN 0909 - 4288, Road Directorate, Copenhagen, 1996.

[2] Riis, K. and Haugaard, M.: "HETEK - Curing - Phase 1: Laboratory Tests". Road Directorate report No. 73, Copenhagen, 1997.

[3] Nielsen, T. and Haugaard, M.: "HETEK - Curing - Phase 2: Evaluation of Test Results". Road Directorate, report No. 100, Copenhagen, 1997.

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[8] Freiesleben Hansen, P. & Pedersen, E. J.: "Vinterstøbning af beton", SBI-anvisning, Statens Byggeforskningsinstitut, 1982.

[9] Pedersen, E.S. et. al.: "HETEK - Styring af revner i ung beton - Anvisning", Vejdirektoratet, Report nr. 119, 1997.

Appendix 1:

Nomograms - Water loss by evaporation

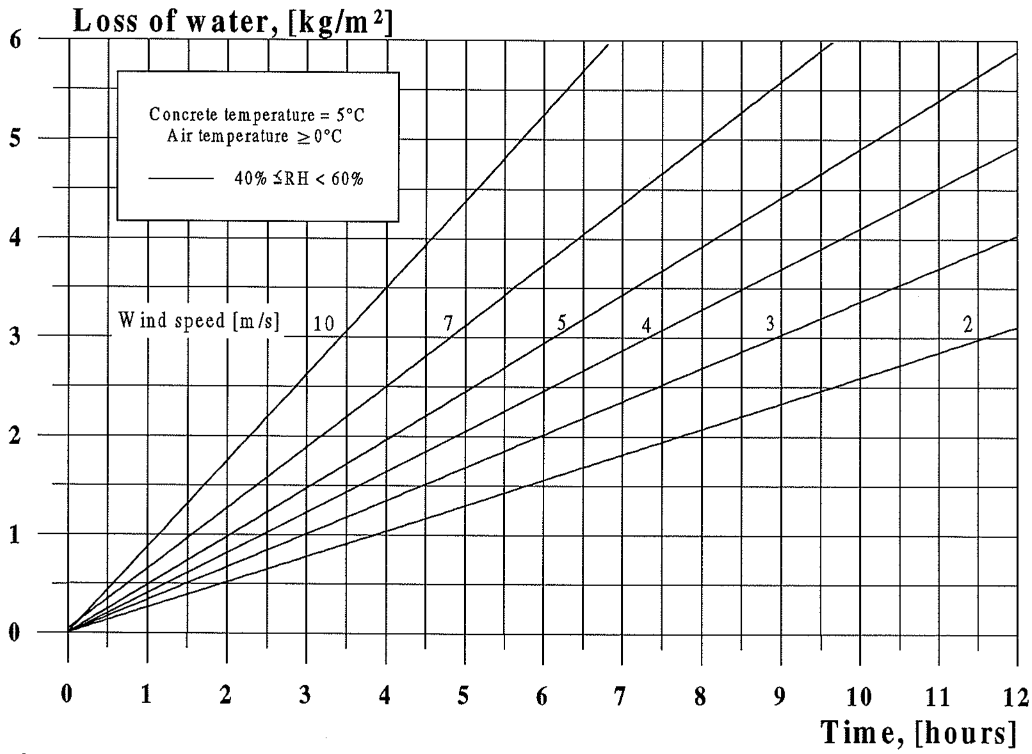


Figure B1.1.

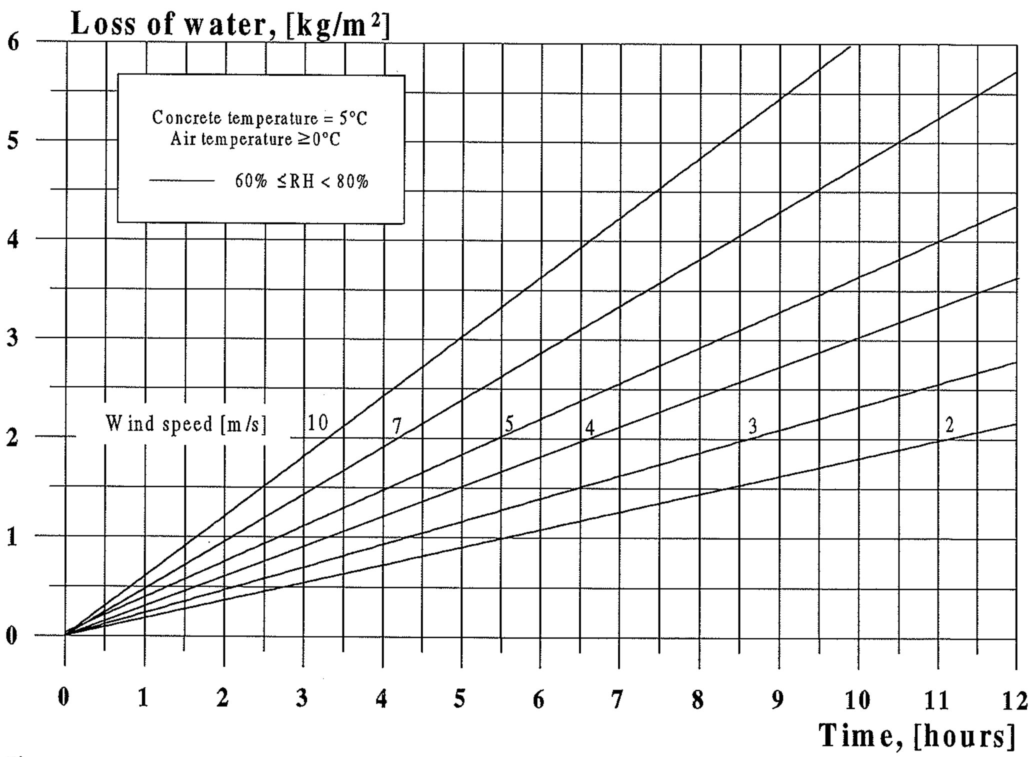
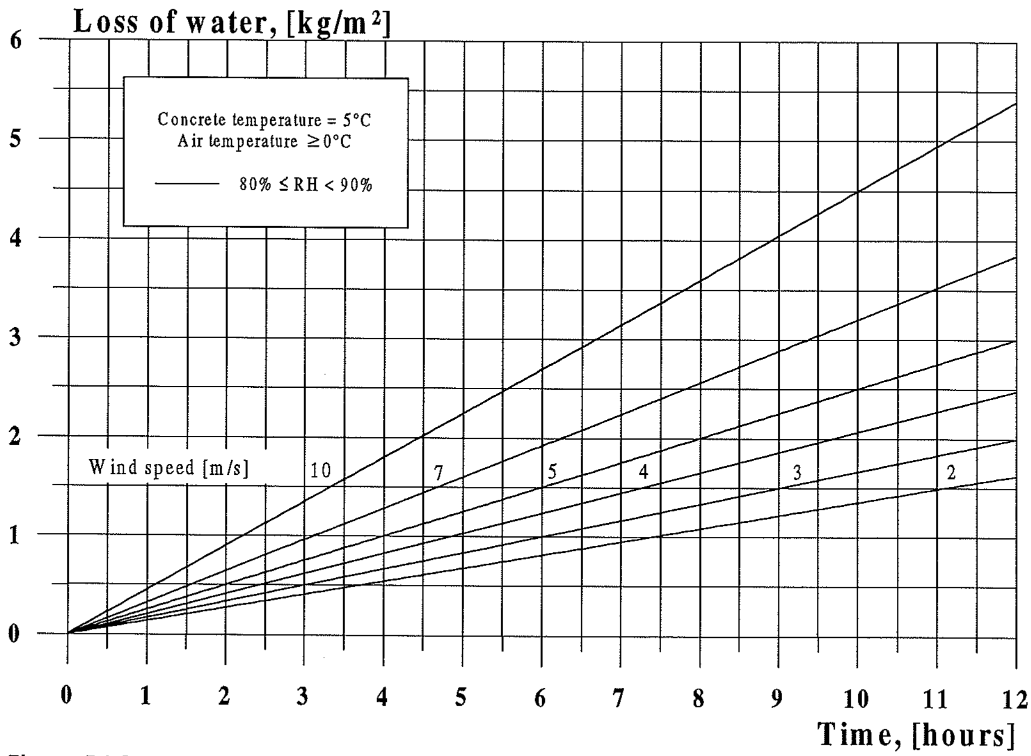


Figure B1.2.



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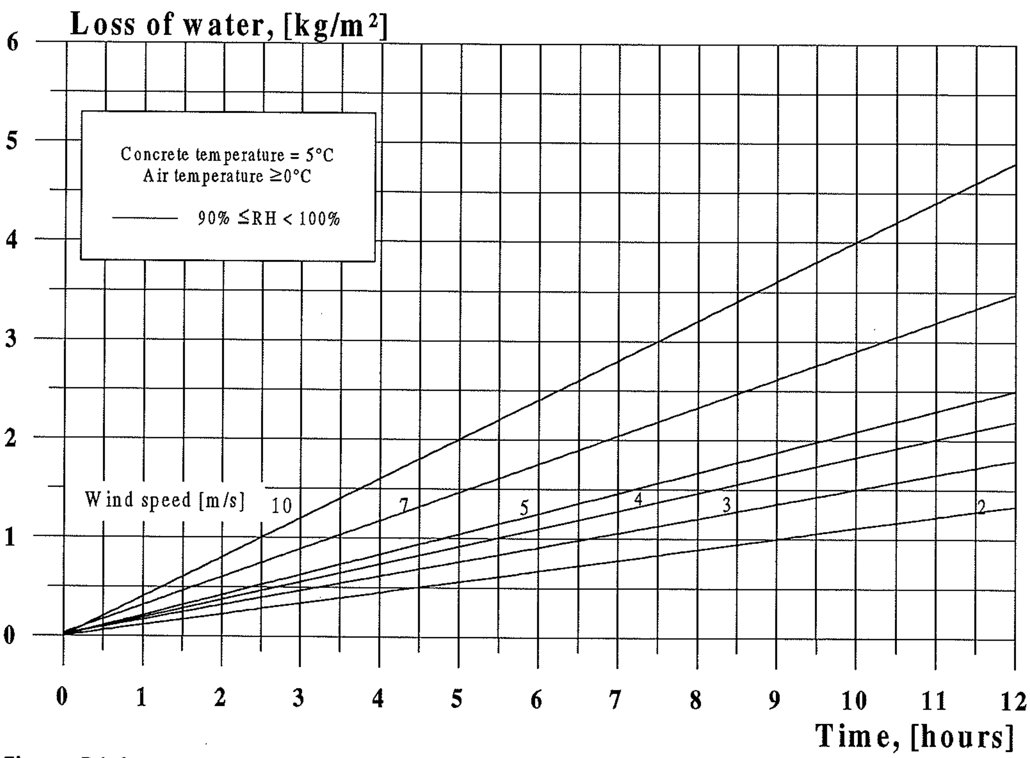

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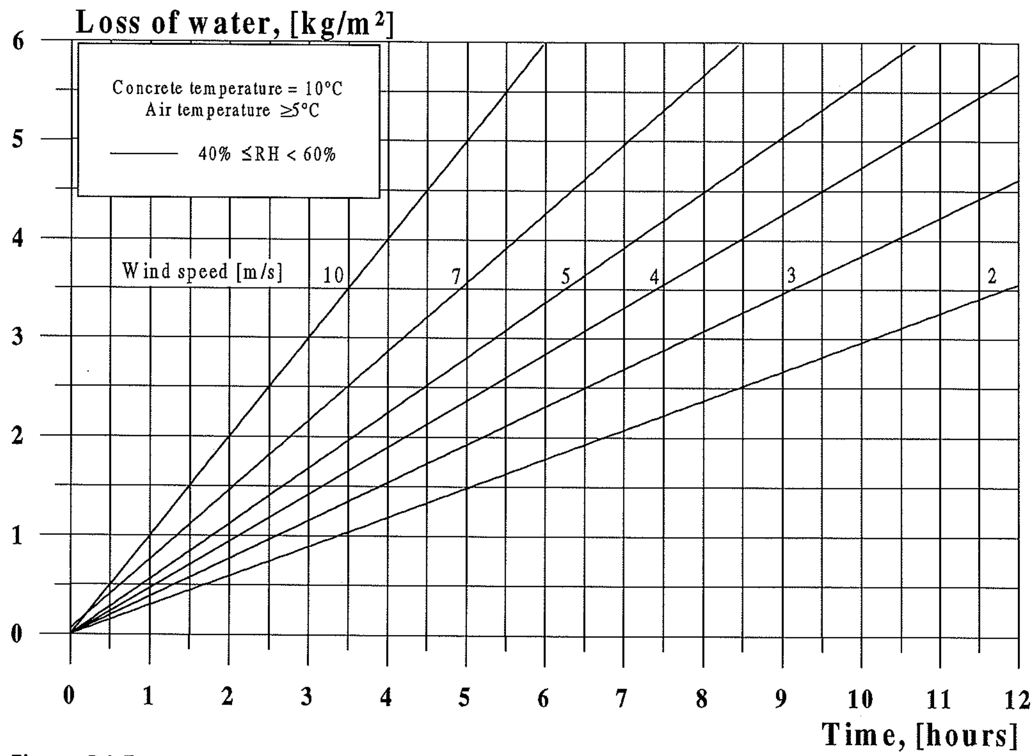

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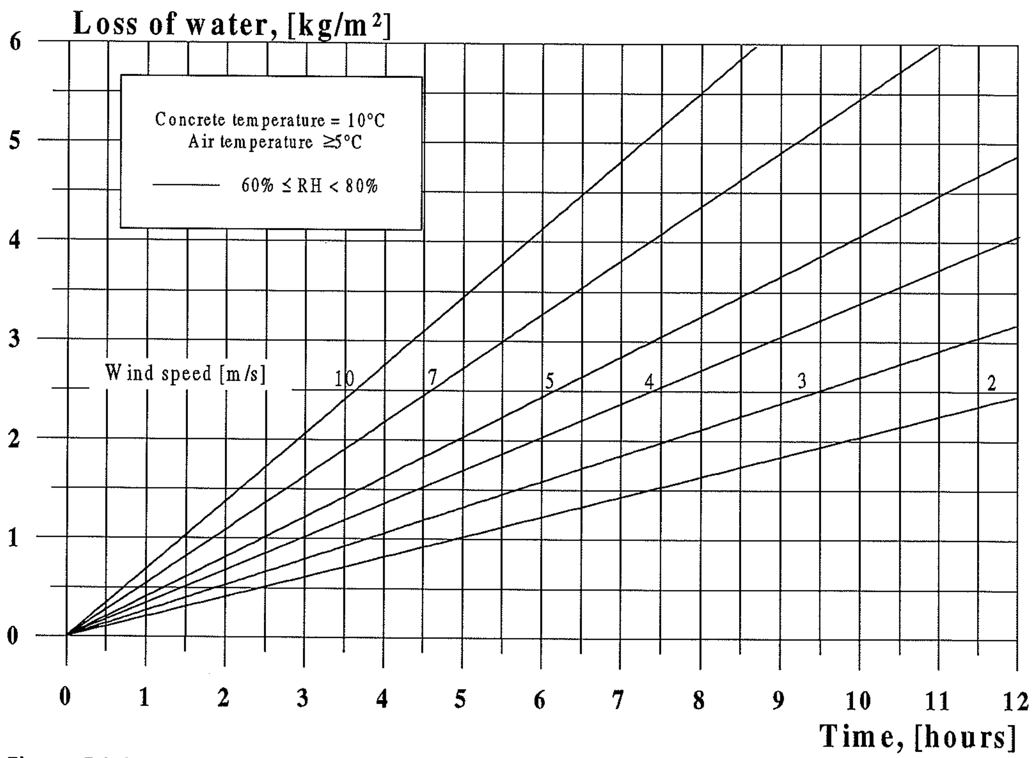
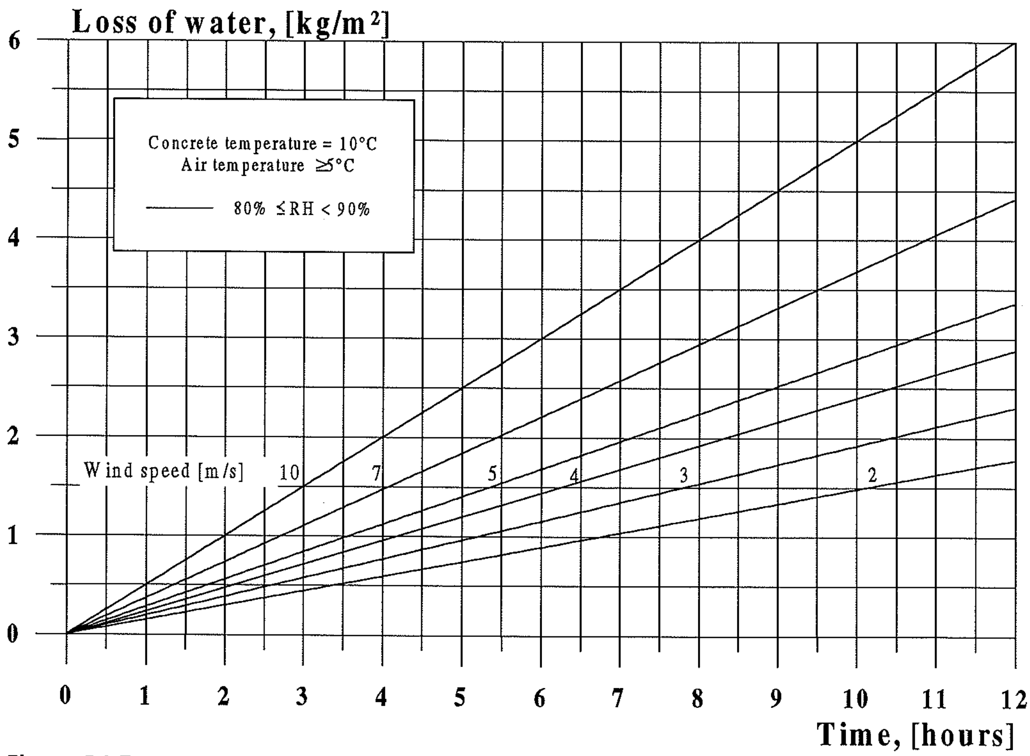


Figure B1.6.



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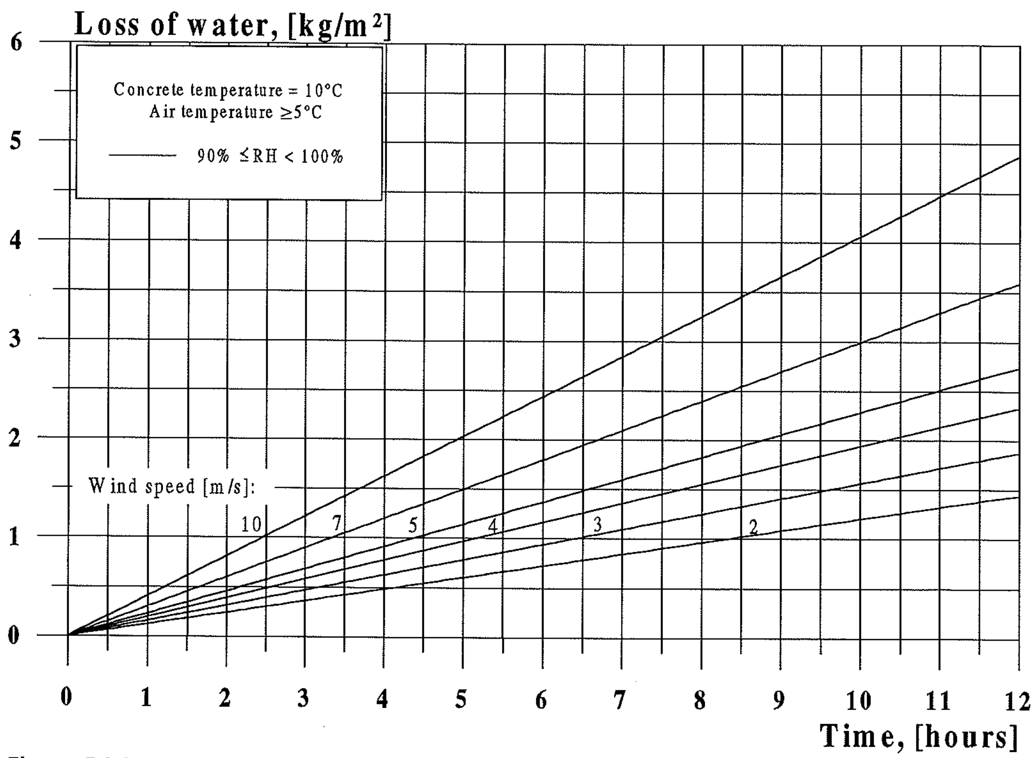

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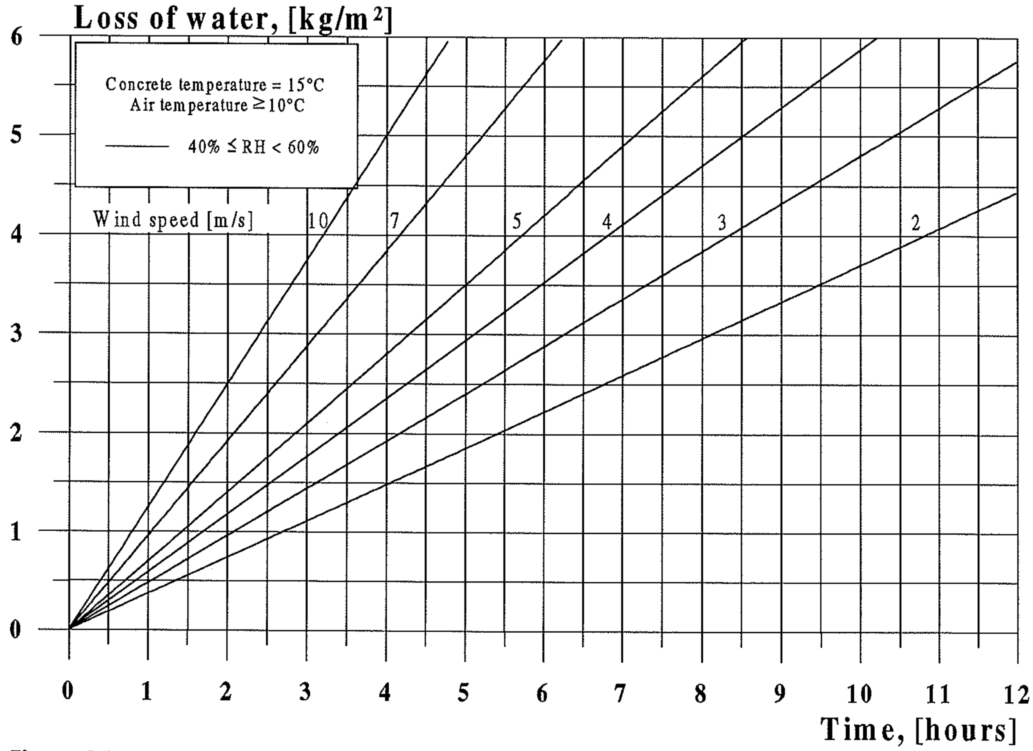

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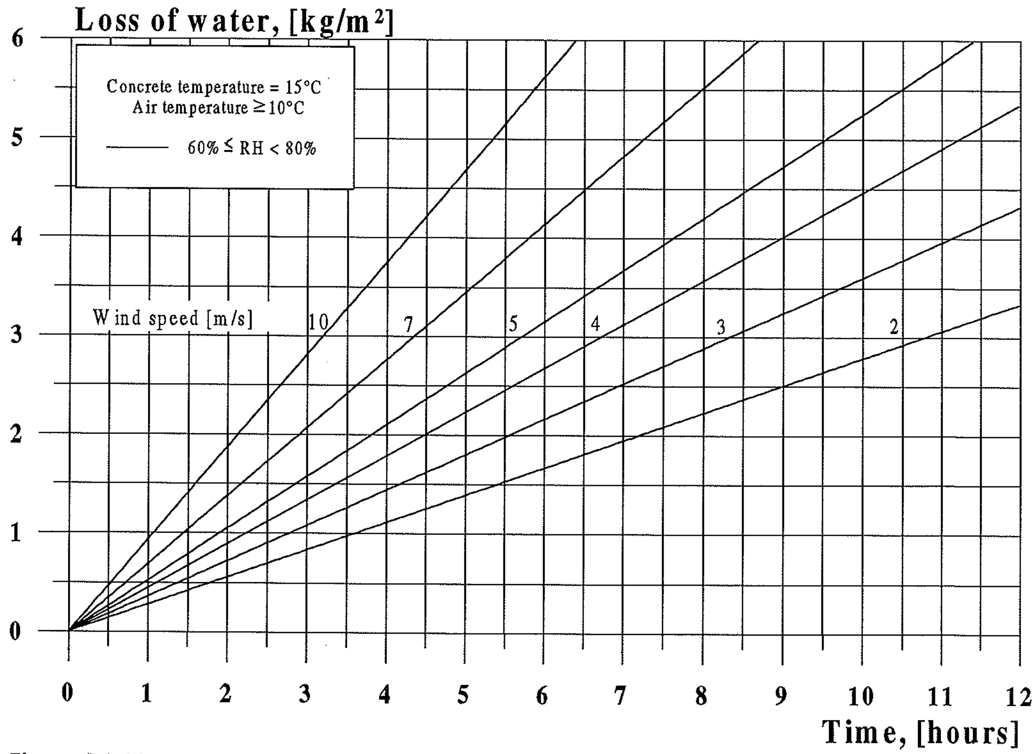


Figure B1.10.

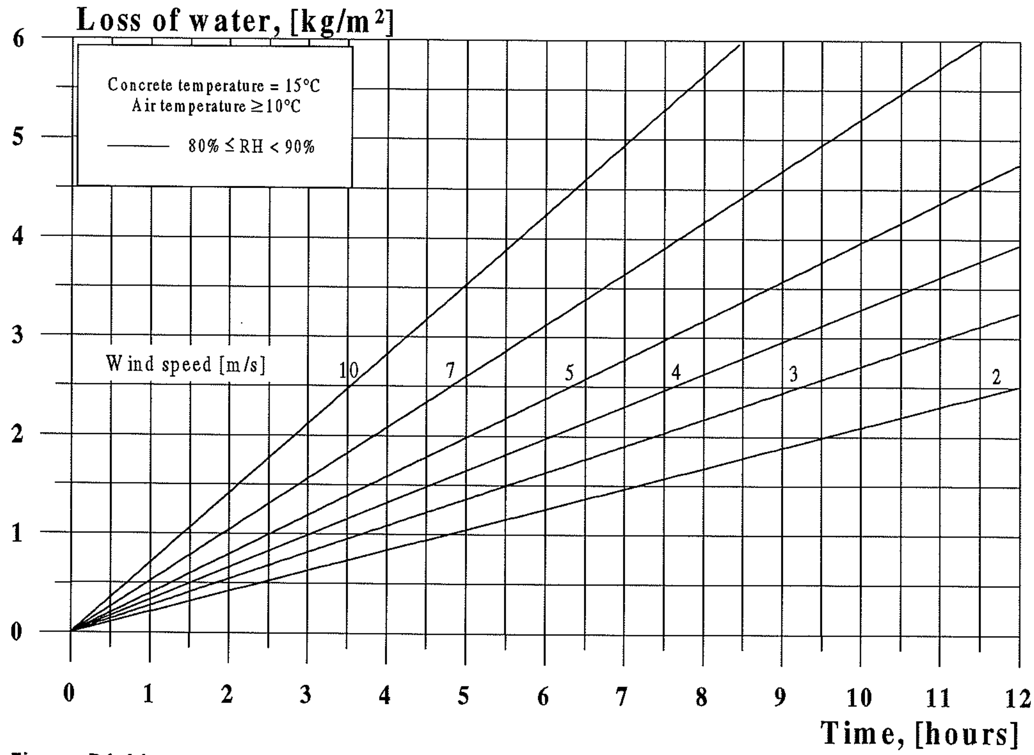
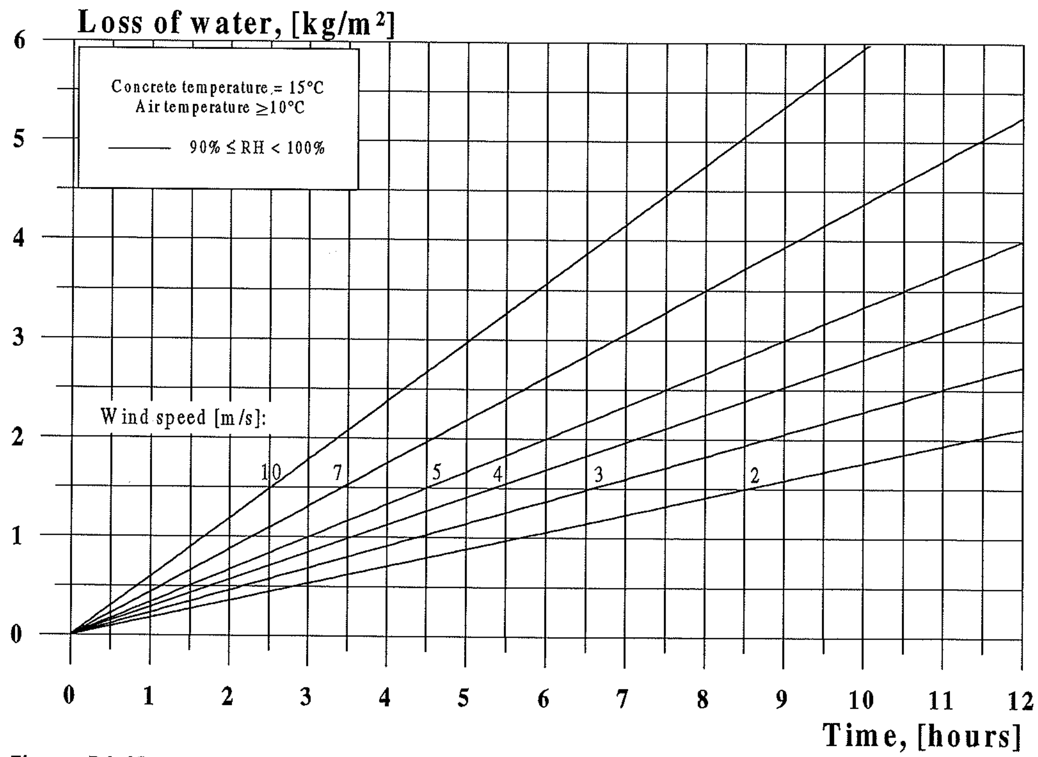


Figure B1.11.



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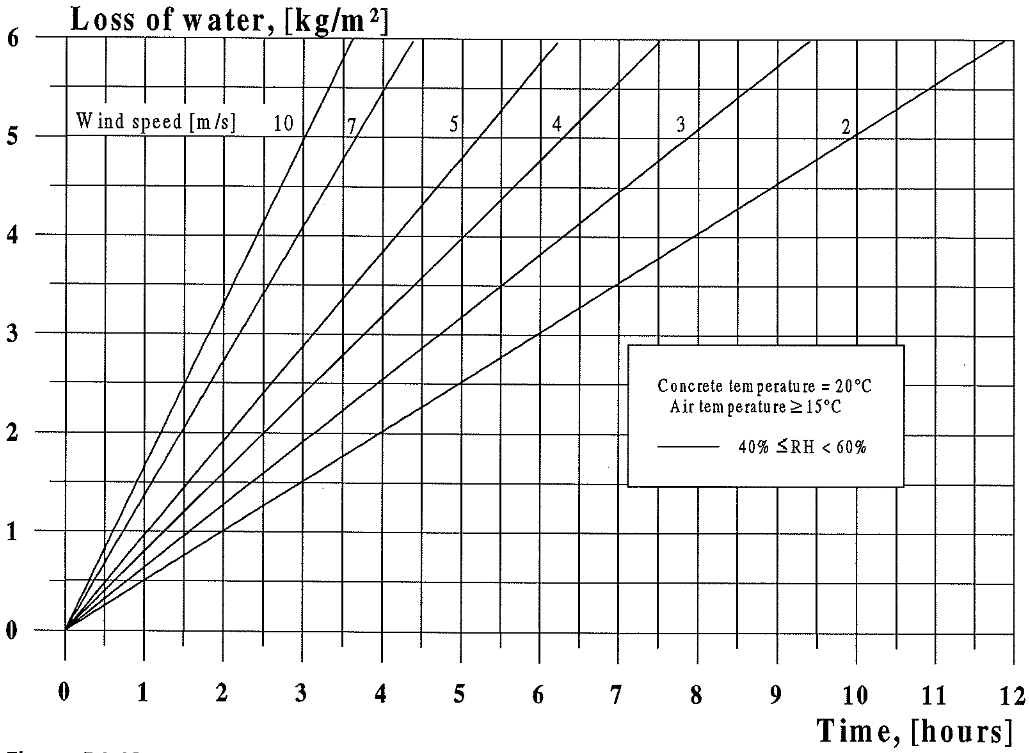

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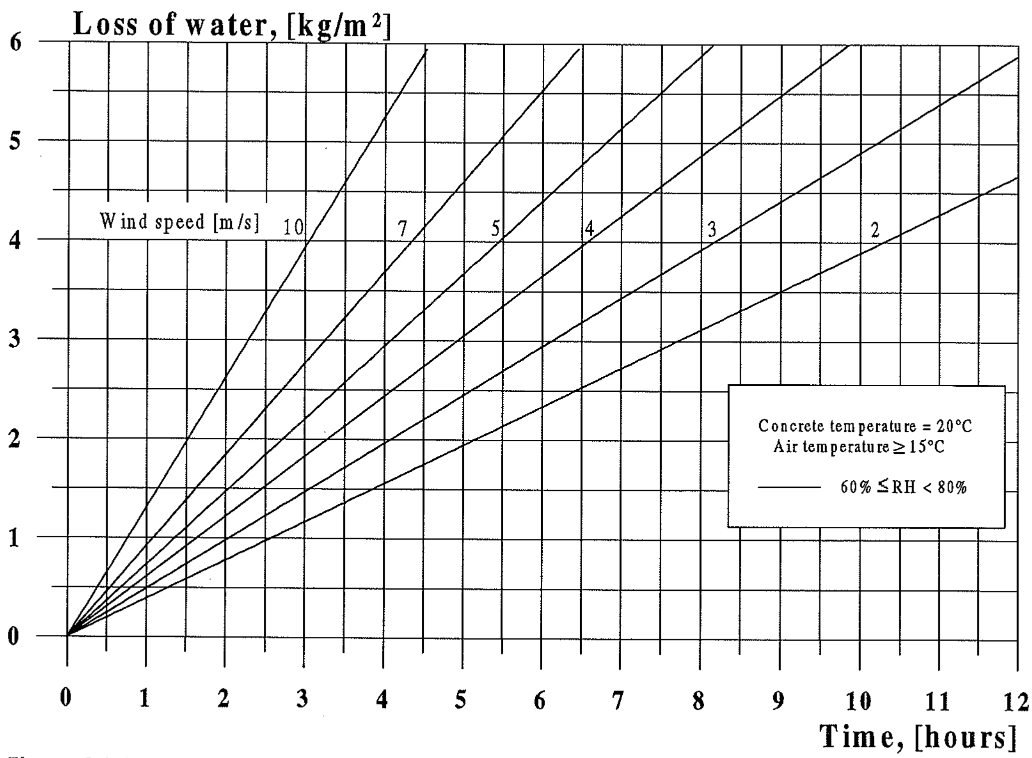

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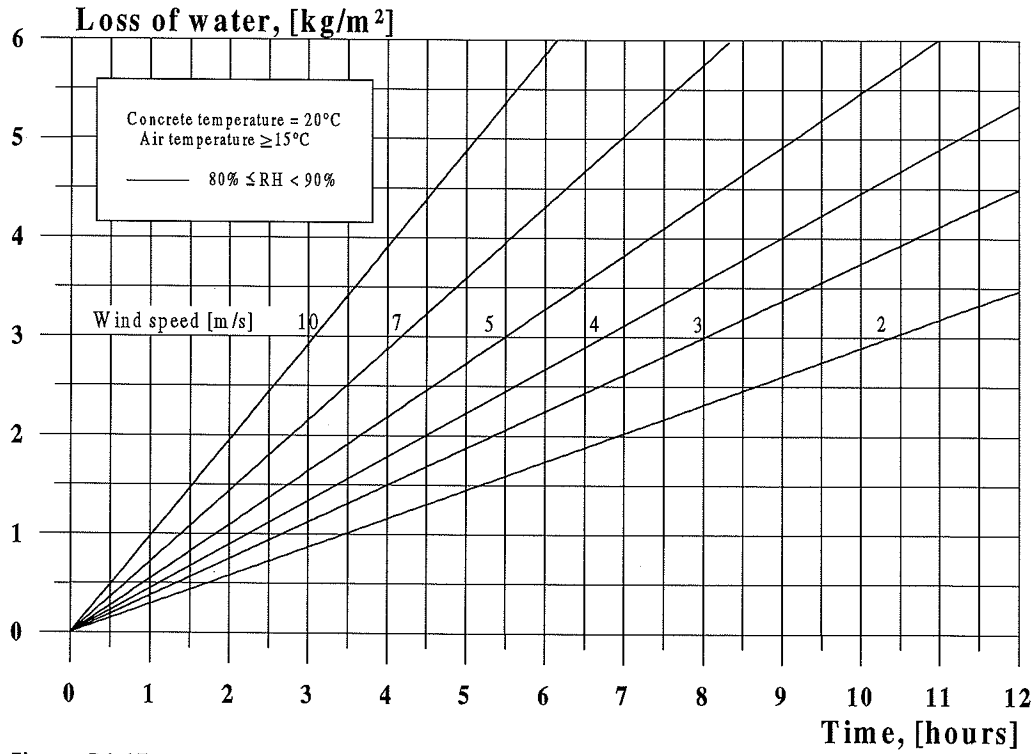

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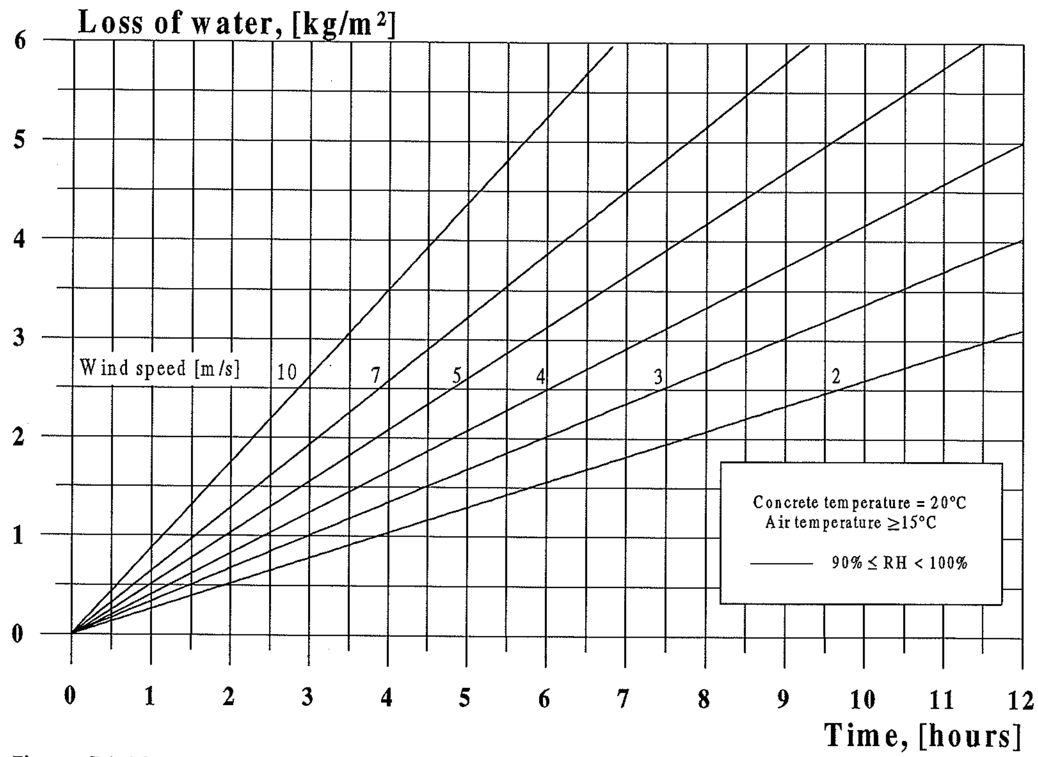

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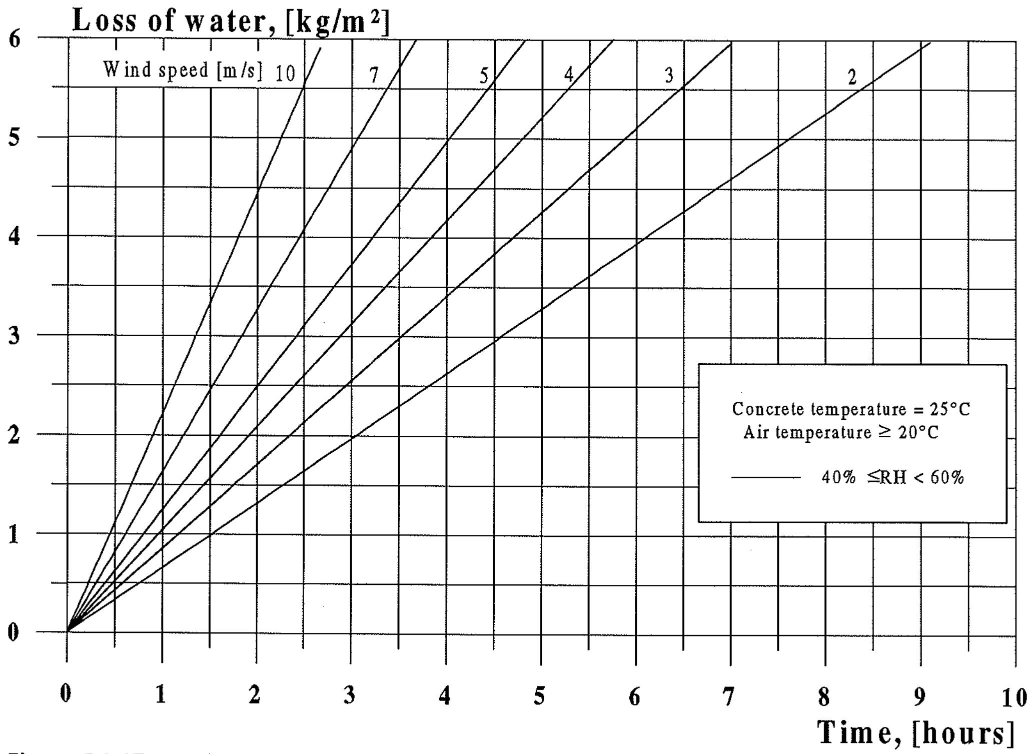

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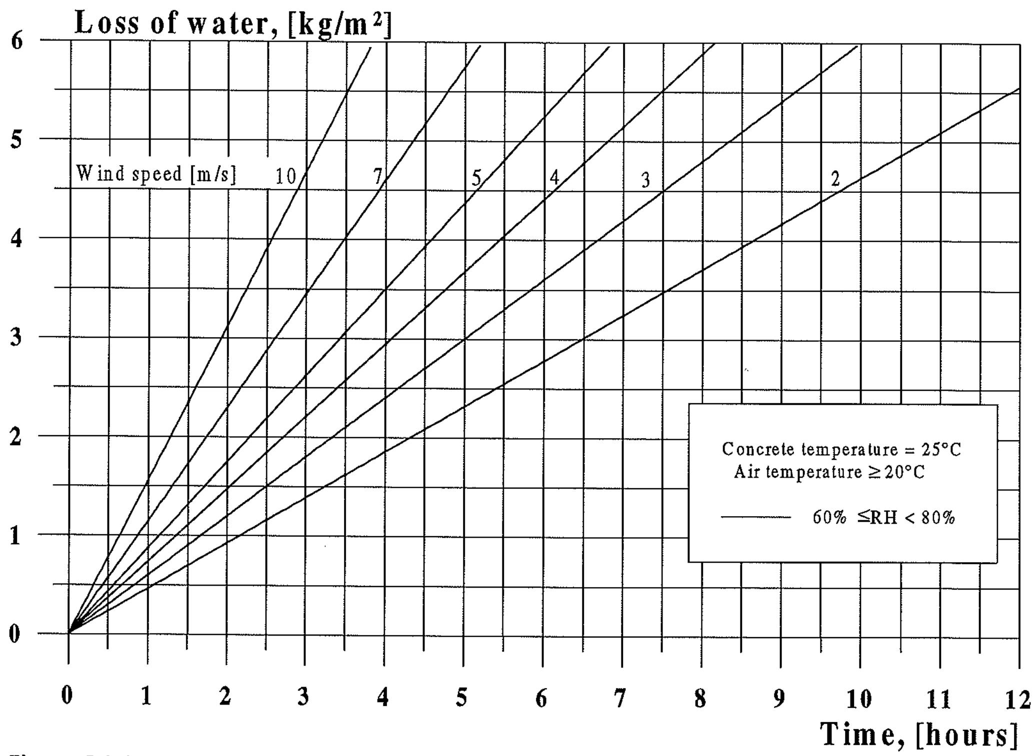

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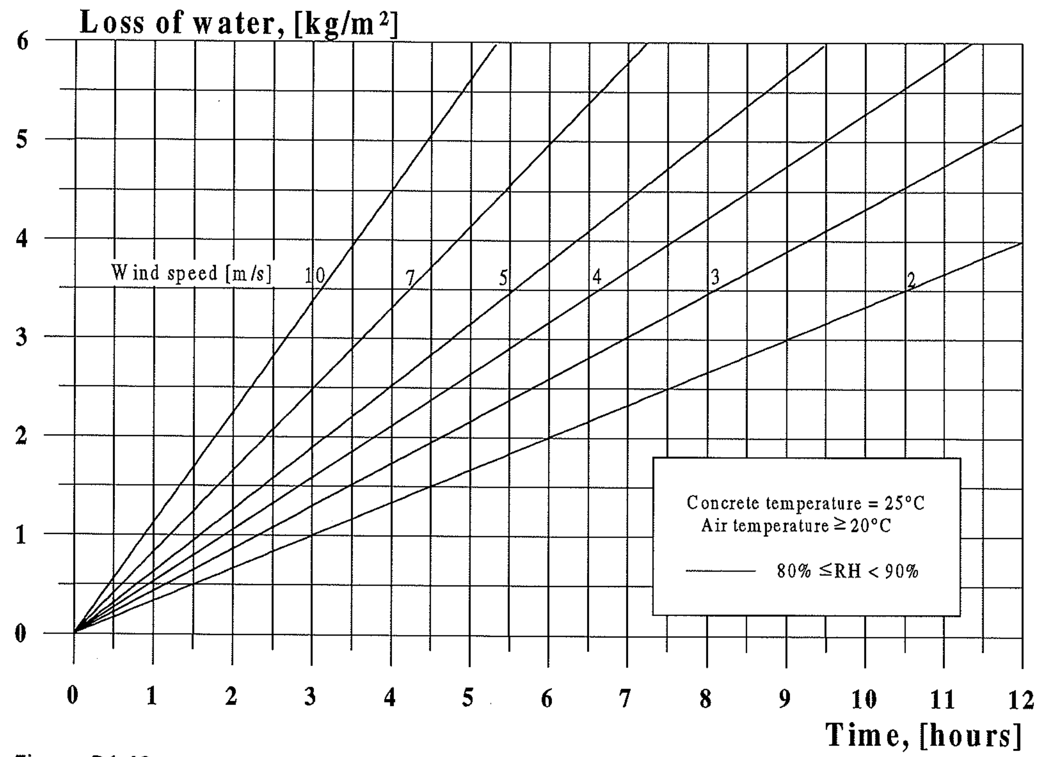

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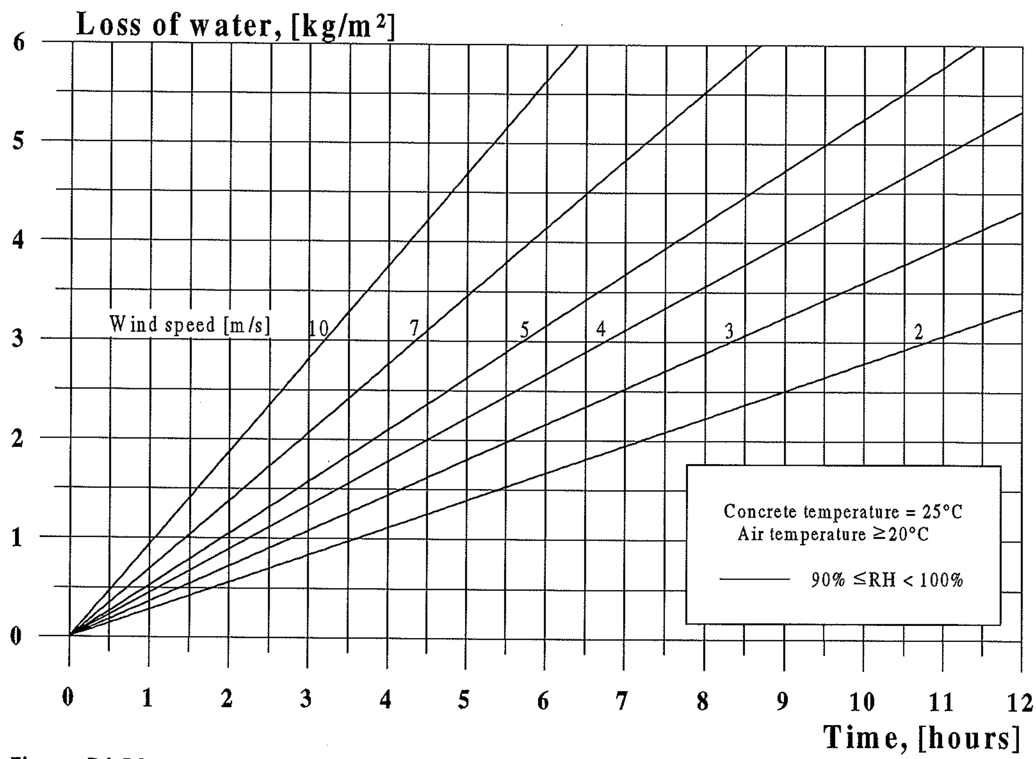

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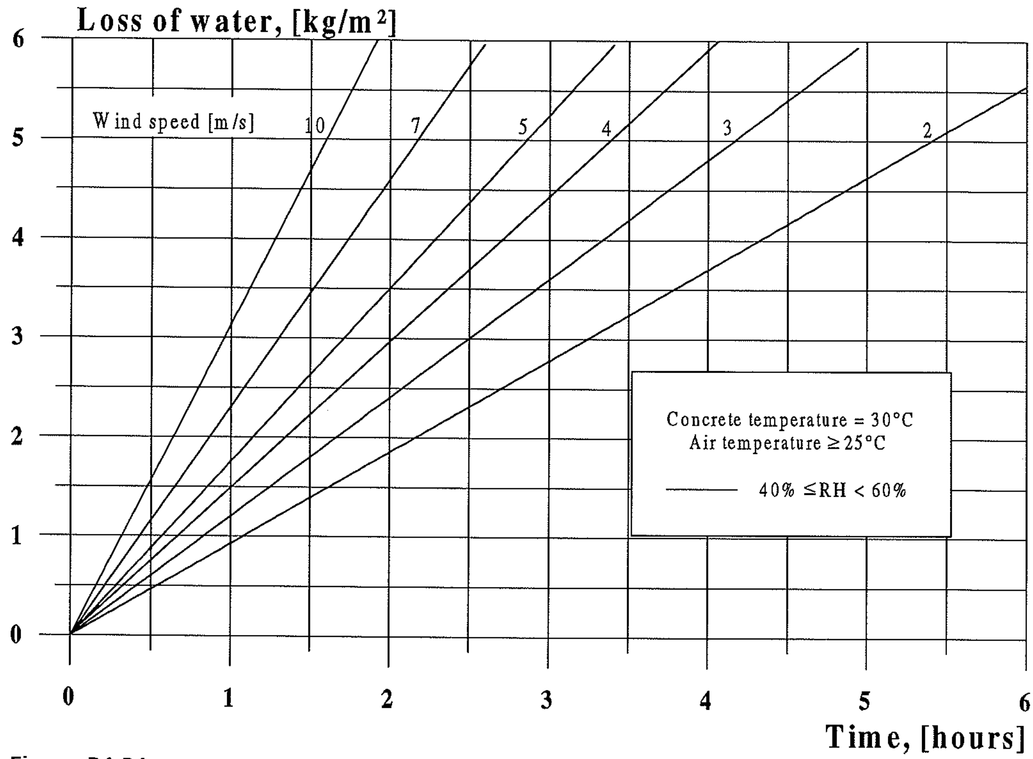

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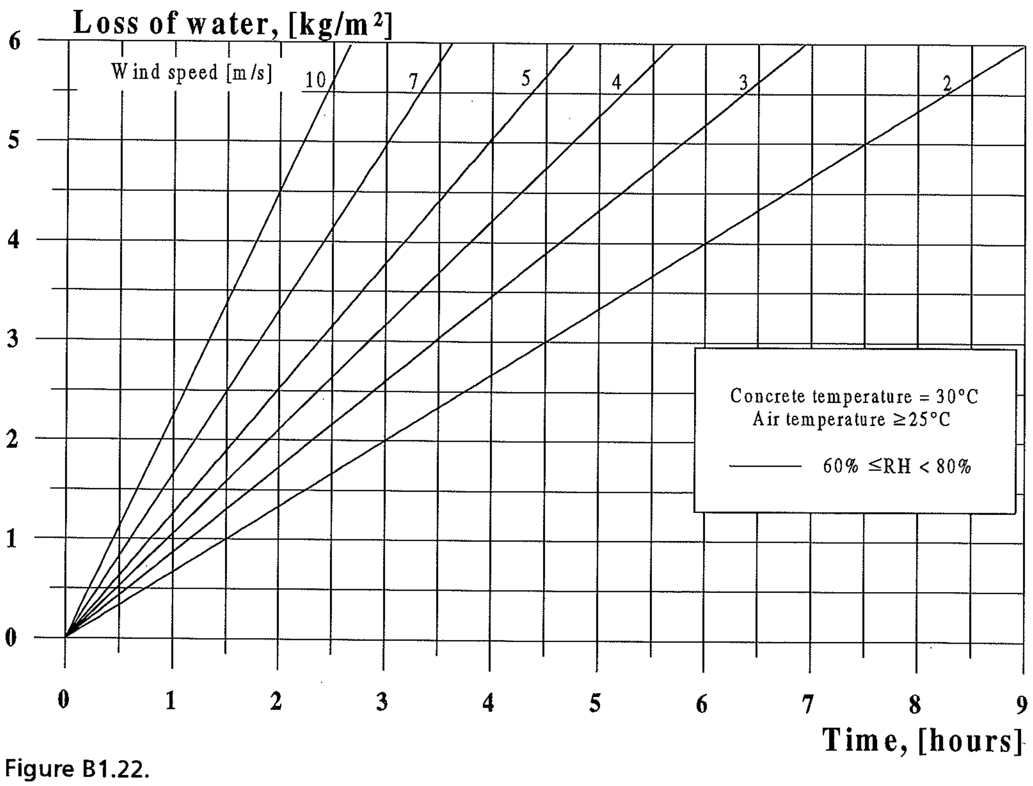


Figure B1.22.

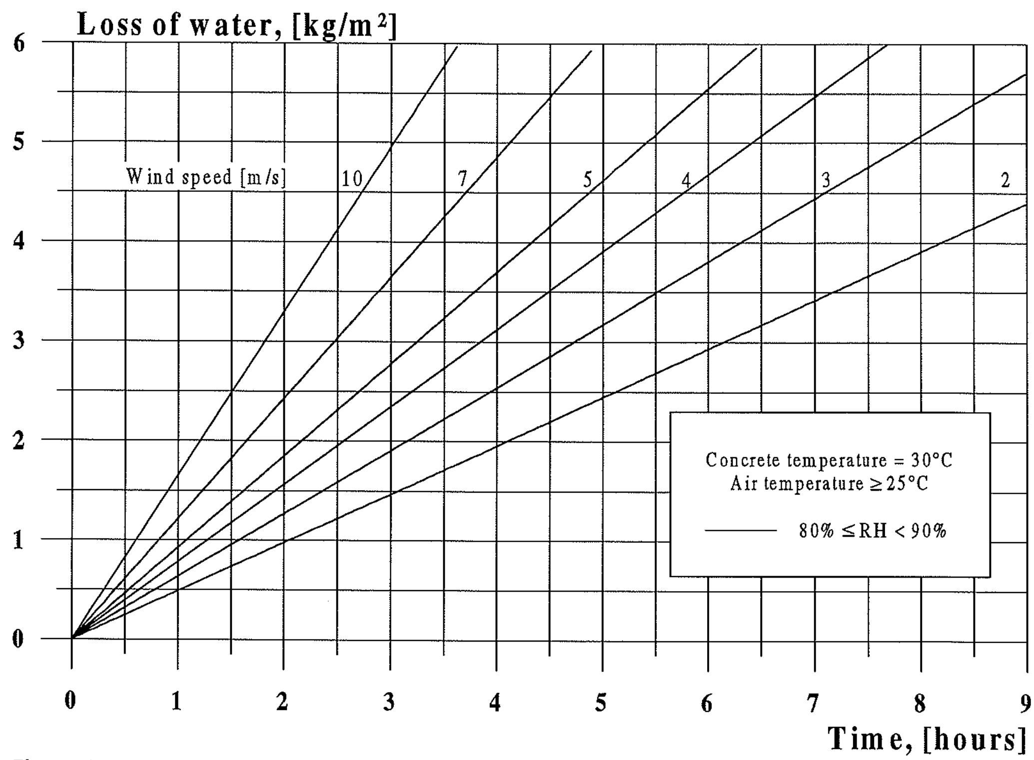


Figure B1.23.

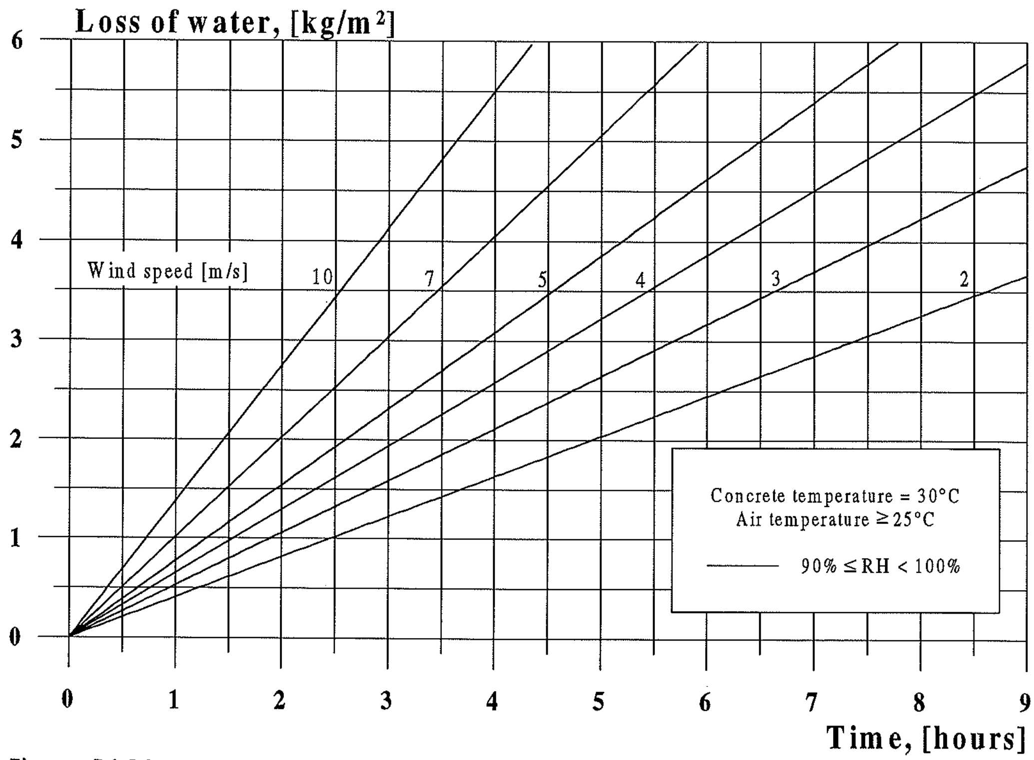
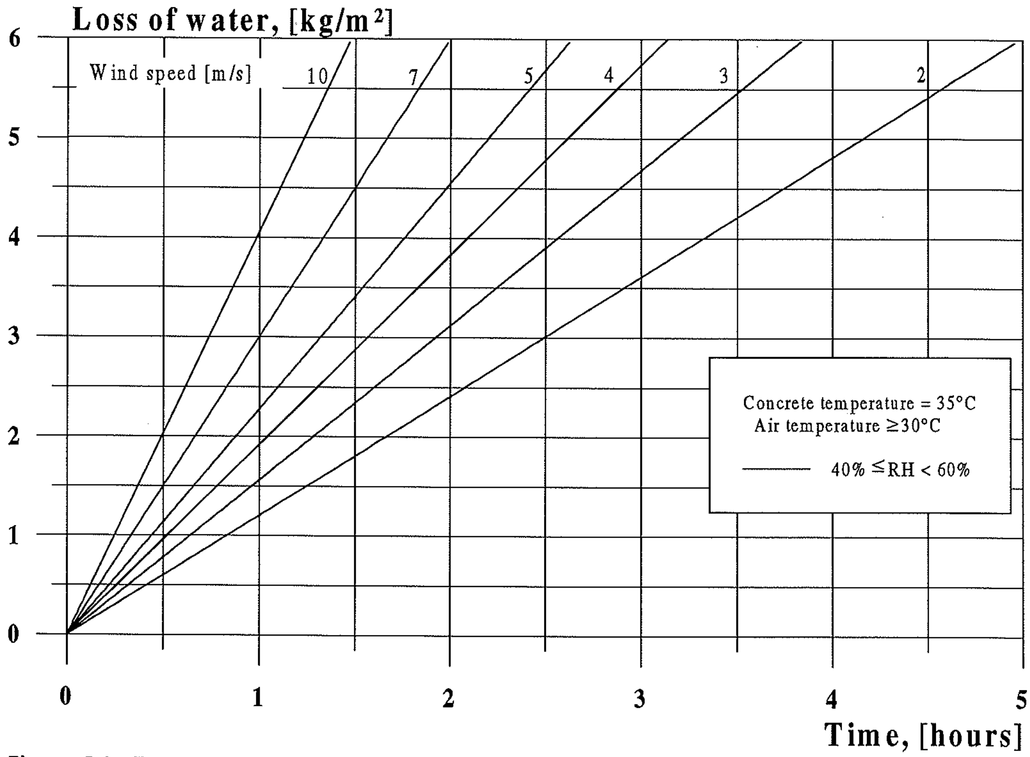


Figure. B1.24.



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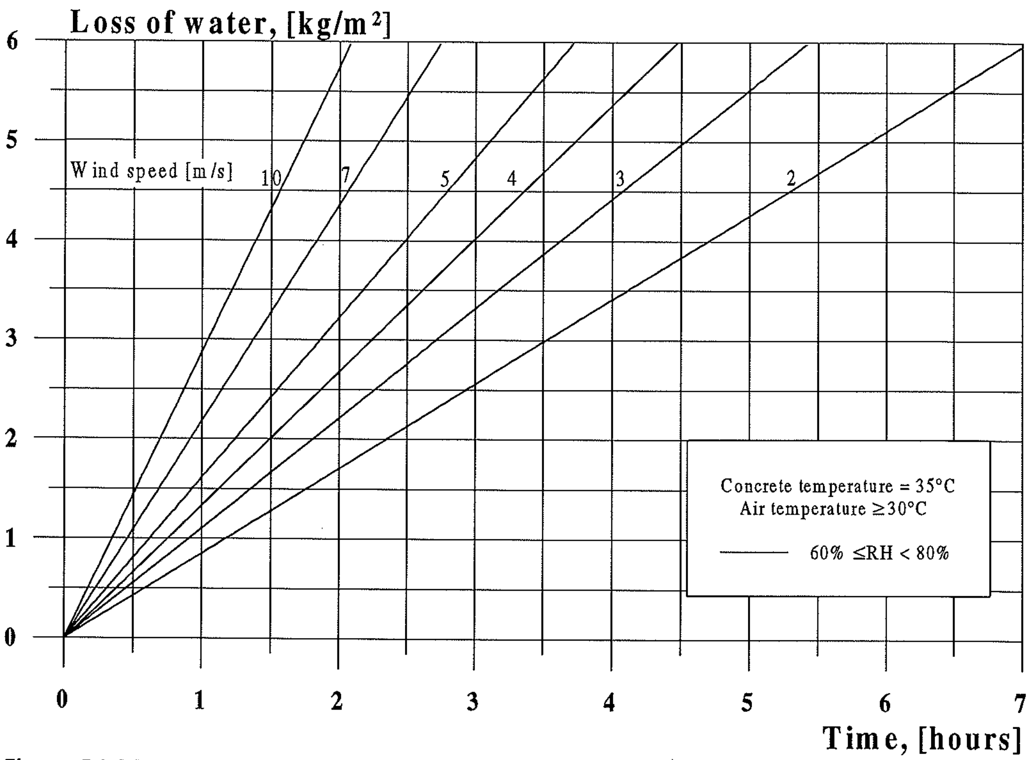

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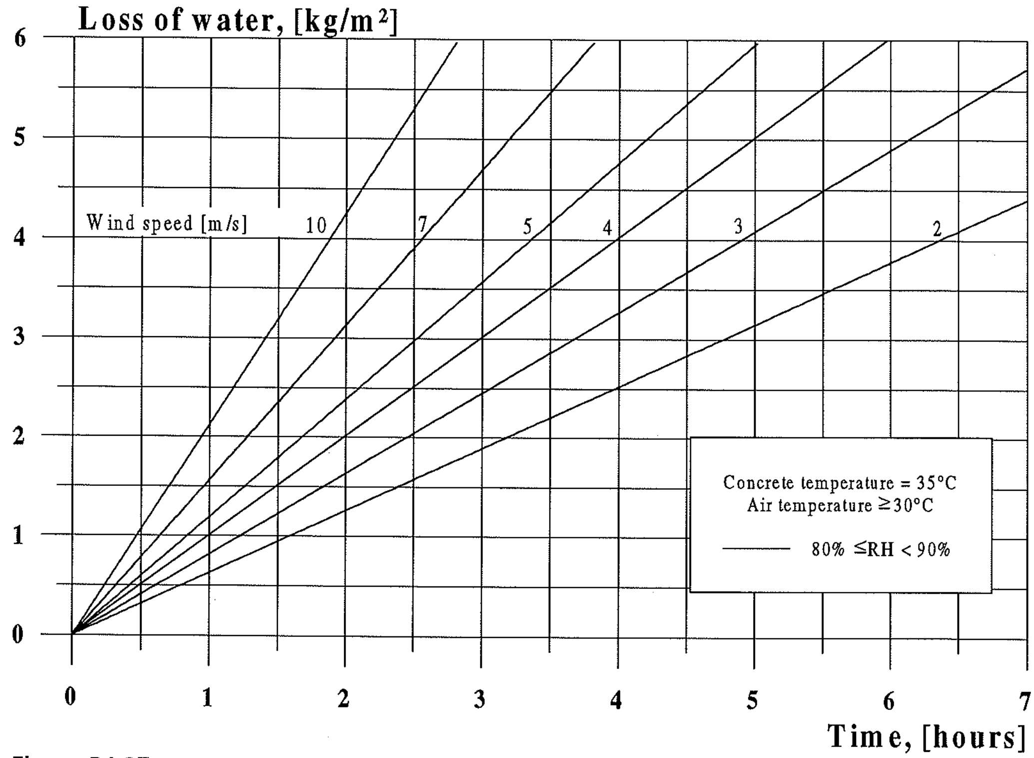

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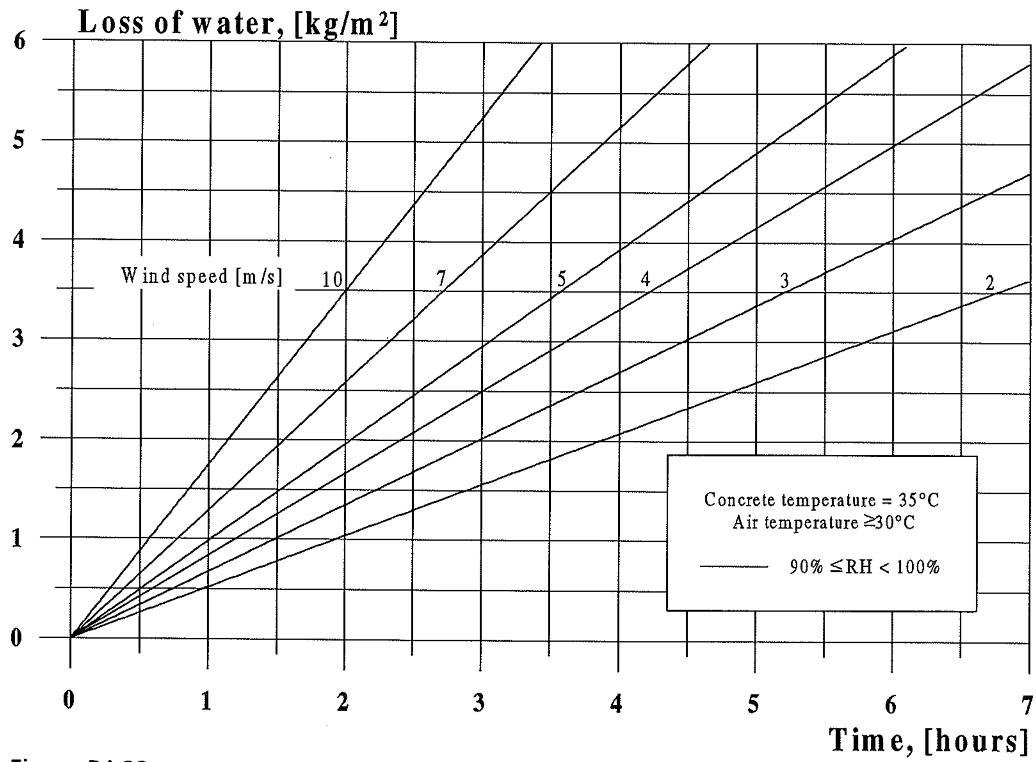


Figure B1.28.

Appendix 2:

Summary of curing methods

Material/method	Advantage	Drawback
Plastic film. Tarpaulin. Mineral wool mats. Polystyrene foam plastic.	• Flexible methods, best on horizontal surfaces. Tarpaulin is also good on vertical surfaces • Can be used on both hardening and hardened concrete surfaces • No drawbacks on subsequent curing. • Good working conditions	• Risk of impression marks in fresh concrete. Greater risk from tarpaulin than from plastic film. Mineral wool mats can not be used on fresh concrete. Polystyrene foam plastic boards may give problems. • Not qualified for use on undersides. Plastic film is less qualified on vertical, stripped sides • May give discoloration from condensation • Risk of forming wind tunnels
Tarpaulin. Mineral wool mat. Polystyrene foam plastic.	• Easy to handle • Great reusability • Great durability and low maintenance costs	
Mineral wool mat. Polystyrene foam plastic.		• Normally other kinds of curing are neeeded at casting
Plastic film	• No maintenance (normally thrown away after use)	• Limited durability and reuse
Mould of varnished wood, plywood or steel. Timber formwork. Mould with form liner.	• No drawbacks on subsequent curing • Good working conditions	• Whenever a long curing time is required other kinds of curing must be introduced • The concrete may stick to the mould after a long curing period • At construction joints special precautions are needed
Mould of varnished wood, plywood or steel. Timber formwork	• Efficient methods	
Timber formwork		• Risk of drying out of the mould
Mould with form liner	• Improved quality and appearance of the surface	• Mounting is difficult • Low reuse • Increased costs

Table B2.1. Advantages and drawbacks from using non-permeable membranes and moulds for curing purpose

Material/method	Advantage	Drawback
Curing compound. Wetting.	• Easy to apply • Can be used as supplementary curing after demoulding • Good working conditions • Good economy	
Curing compound.		• Drawbacks on subsequent curing • Special requirements at construction joints
Wetting.	• Gives a good hydration of the concrete surface • No drawbacks on subsequent curing • Good to use at construction joints	• Increased supervision is required • Risk of plastic shrinkage cracks when started too late • Risk of thermal cracks • Risk of stains • Risk of damage caused by freezing • Risk of dilution of concrete
Climatic control	• Easy to handle indoor • Gives a steady hardening • No drawbacks on subsequent curing • Good economy when used outdoor	• Increased demands on control • Special demands on working facilities • Poor working conditions
Liquid additive. (polymer)	• Easy to handle • Gives an even hardening • Good working conditions	• The method is not fully tested on concrete • Possible risks of drawbacks on subsequent curing • Bad economy
Fibres	• Easy to use • Good working conditions	• Effect on pore structure not documented • Small economic importance • The efficiency depends on type and amount of fibres • Fibres may reduce plastic shrinkage cracks but do not prevent evaporation • Additional curing is required

Table B2.2. Advantages and drawbacks from using the following materials and methods for curing: Curing compound, wetting, climate control and additives.

Material/ method	Planning	Documentation
Plastic film. Tarpaulin. Mineral wool mats. Polystyrene foam plastic.	• Calculation of the time for starting the curing • Calculation of the required period of curing • Curing materials ready for use before casting is started • Boards or sand must be used for securing the cover	• Visual inspection of the efficiency of the curing materials • Record of the time for applying the material • Record of total period of curing, measurement of temperature and calculation of maturity
Mould of varnished wood, plywood or steel. Timber formwork. Mould with form liner.	• Calculation to predict the time when the mould can be removed • Establishing the measures to be taken after demoulding • Check the tightness of the mould before casting	• Record of total period in mould and calculation of maturity • Record of type and extent of measures taken after demoulding
Curing compound.	• Calculation of the proper time to apply the curing compound • Measures to ensure the quality • Check the tightness of the mould before casting	• Record of actually applied quantity
Wetting.	• Considering supplementary curing methods to prevent plastic shrinkage • Calculation to predict the time, when the wetting can be stopped • Measures to ensure the efficiency	• Record of measures taken to keep the concrete wett and quantities of water used • Record of total period of wetting and calculation of maturity
Climatic control.	• Calculation to predict the time when the climate control can be stopped • Control of the efficiency by weighing test specimens	• Record of temperatures of air and concrete, relative humidity of air and wind velocity • Calculation of maturity
Liquid additive. (polymer)	• Control of the efficiency by weighing test specimens	• Documentation on the polymer used
Fibres	• Planning measures as indicated above	• Documentation is carried out after use

Table B2.3. Planning and documenting curing methods and materials

Appendix 3:

Forms to be used in planning and inspection

Planning 1: Concrete	
File name:	File No.:
Structural component:	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date:	Signature:

Concrete composition			
Material	kg/m^3	% of binder	Comments
Cement, C			
Fly ash, FA			
Micro silica, MS			
FA + MS			
Binder = C+FA+MS			
Equiv. w/c =		Environmental class	

Hardening concrete			
	Q_∞, [kJ/kg binder]	τ_e, [hours]	α
Adiabatic heat development			
Setting time, τ_0 = hours			

Planning 2: Time to start the curing	
File name:	File No.:
Structural component:	
Control section name:	Control plan reference:
Appendix reference:	Drawing reference:
Date:	Signature:

Maximum time before curing is started		
Maximum amount of water allowed to evaporate before curing = kg/m^2		
Concrete temperature = °C	Air temperature = °C	Relative humidity of air = %
Wind velocity = m/s	Thickness of concrete layer = m	

Comments/calculations:
Calculated maximum time before curing is started = hours

Or:

From table 2.2: Maximum time before curing is started = hours	Indoor activity		Outdoor activity	

Planning 3: Minimum period of curing	
File name:	File No.:
Structural component:	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date:	Signature:

Minimum required degree of reaction R before curing can be stopped =	%

The corresponding maturity M is determined in one of the following three ways:

		Comments	
Calculation of $M = \tau_e/(-\ln(R))^{1/\alpha} =$	hours		
Or:			
M is read from a graph of the heat development:	hours		
Or:			
M is taken from table 2.4:	hours	If the setting time $\tau_0 \leq 5$ hours	
$M = (M \text{ as above}) + (\tau_0 - 5 \text{ hours}) =$	hours	If the setting time $\tau_0 > 5$ hours	

Comments:

Planning 4: Temperature and maturity	
File name:	File No.:
Structural component:	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date:	Signature:

Temperature at casting [°C]	Density [kg/m^3]	Specific heat [kJ/kg°C]	Thermal conductivity [kJ/m·h°C]

Binder content [kg/m^3]	Wind velocity [m/s]	Minimum air temperature [°C]	Maximum air temperature [°C]

Time [hours]	Insulation 1	Insulation 2	k1 [kJ/m^2·h °C]	k2 [kJ/m^2·h °C]

Inspection 1: Curing schedule			
File name:		File No.:	
Structural component:			
Control plan section:		Control plan reference:	
Appendix reference:		Drawing reference:	
Date:	Signature:		

Curing schedule					Initials:
Hours	Maturity hours	Curing			Comments
		Type of curing	Surface		
			Free	Form	
0		Time of casting			

Inspection 2: Record of curing

File name:	File No.:
Structural component:	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date:	Signature:

Record of curing | Initials:

Hours	Maturity hours	Curing			Comments
		Type of curing	Surface		
			Free	Form	
0		Time of casting			

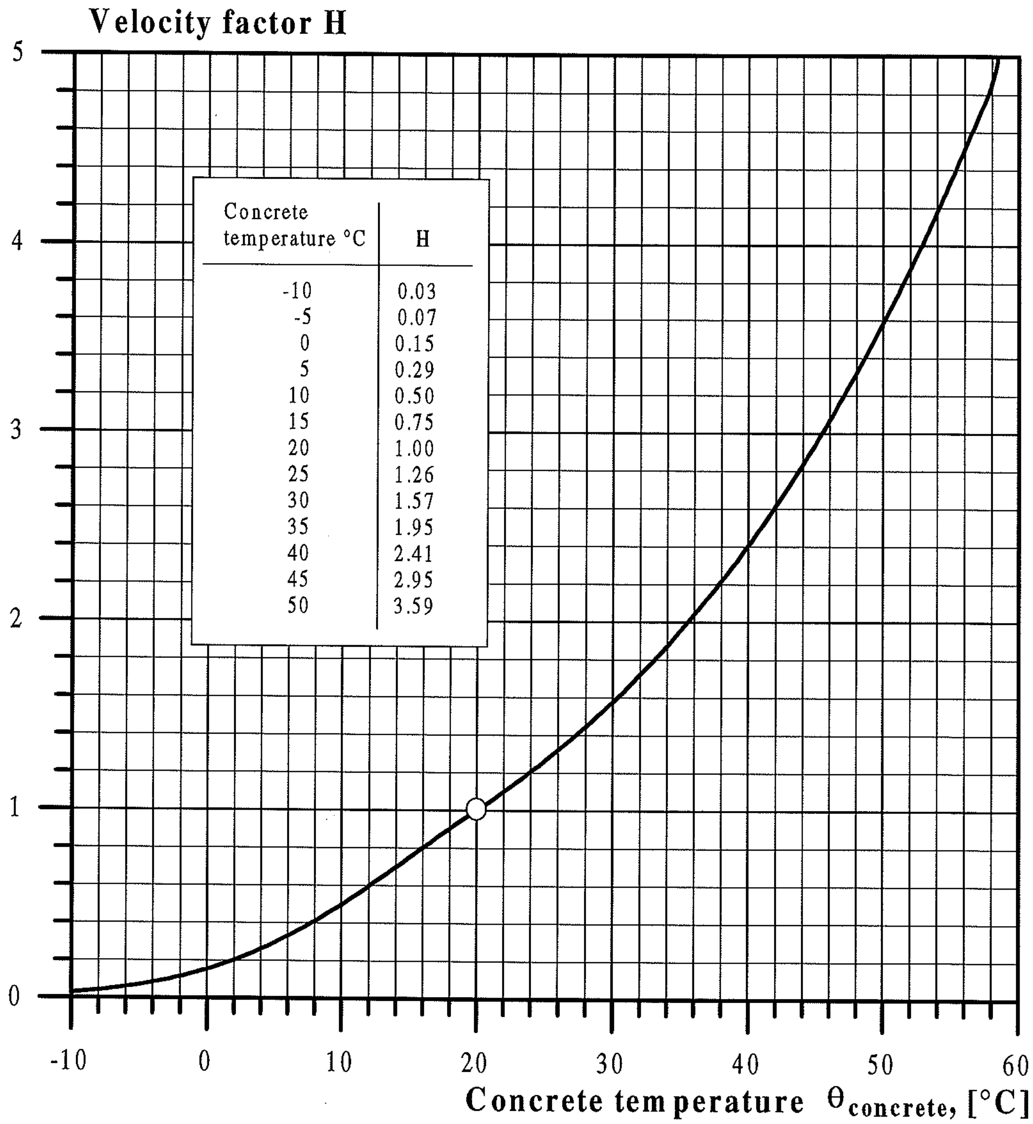
Comments:

Inspection 3: Calculation of maturity	
File name:	File No.:
Structural component:	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date:	Signature:

h [hours]	$\theta_{concrete}$ [°C]	Δt [hours]	$\overline{\theta}_{concrete}$ [°C]	H	ΔM [hours]	M [hours]

Appendix 4:

Velocity factor H for calculation of maturity



Concrete temperature °C	H
-10	0.03
-5	0.07
0	0.15
5	0.29
10	0.50
15	0.75
20	1.00
25	1.26
30	1.57
35	1.95
40	2.41
45	2.95
50	3.59

$$H = \exp\left(\frac{E}{8.314}\left(\frac{1}{293} - \frac{1}{273 + \theta_{concrete}}\right)\right) \quad , \quad \text{where:}$$

$$E = \begin{cases} 33500 + 1470\,(20 - \theta_{concrete}) \;, \; [\text{J/mol}] \;, \; \text{for } \theta < 20°\text{C} \\ 33500 \;, \; [\text{J/mol}] \;, \; \text{for } \theta \geq 20°\text{C} \end{cases}$$

Appendix 5:

Examples

Appendix 5.1:

Concrete floor cast during August

Planning 1: Concrete (Form B5.1.1)	
File name: Hetek - Floor. Concrete A.	File No.: Example 1. Floor cast during August: Typical climate.
Structural component: 0.25 m floor	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 14/3-1997	Signature: JXS

Concrete composition			
Material	kg/m^3	% of binder	Comments
Cement, C	285		Information on this side is taken from the
Fly ash, FA	60		BBB-form of the concrete
Micro silica, MS	12		
FA + MS	72		
Binder = C+FA+MS	357		
Equiv. w/c = 0.41		Environm. class: Aggressive	

Hardening concrete			
	Q_∞, [kJ/kg binder]	τ_e, [hours]	α
Adiabatic heat development	280	14.2	0.96
Setting time, $\tau_0 =$ 5.5 hours			

Planning 2: Time to start the curing (Form B5.1.2)	
File name: Hetek - Floor. Concrete A.	File No.: Example 1. Floor cast during August: Typical climate.
Structural component: 0.25 m floor	
Control section name:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 14/3-1997	Signature: JXS

Maximum time before curing is started		
Maximum amount of water allowed to evaporate before curing = 1.5 kg/m^2		
Concrete temperature = 20°C	Air temperature = 15.7°C	Relative humidity of air = 85%
Wind velocity = 4 m/s	Thickness of concrete layer = 0.25 m	

Comments/calculations:
The time of starting the curing, 3.8 hours, has been calculated on the basis of a nomogram on the rate of evaporation. It only
has to be documented that the biggest of the two is met. So the curing must be started before 3.8 hours. It is seen that using table 2.2 is more
restricting than the calculation. If the graphes in appendix 1 are used, 3.3 hours are found as starting time.
Calculated maximum time before curing is started = 3.8 hours after casting.

Or:

From table 2.2: Maximum time before curing is started = 1 hour	Indoor activity		Outdoor activity	X

Planning 3: Minimum period of curing (Form B5.1.3)

File name: Hetek - Floor. Concrete A.	File No.: Example 1. Floor cast during August: Typical climate.
Structural component: 0.25 m floor	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 14/3-1997	Signature: JXS

Minimum required degree of reaction R before curing can be stopped = 85%

The corresponding maturity M is determined in one of the following three ways:

		Comments	
Calculation of $M = \tau_e/(-\ln(R))^{1/\alpha}$ =	94 hours	$M = 14.2/-\ln(0.85))^{1/0.96} = 94$ hours	
Or:			
M is read from a graph of the heat development:	hours	Not used if the calculation above is used	
Or:			
M is taken from table 2.4:	120 hours	If the setting time $\tau_0 \leq 5$ hours	
M = (M as above) + (τ_0 - 5 hours) =	120.5 hours	If the setting time $\tau_0 > 5$ hours	$\tau_0 = 5.5$ hours

Comments: The required curing period is 94 hours

Planning 4: Temperature and maturity (Form B5.1.4)

File name: Hetek - Floor. Concrete A.	File No.: Example 1. Floor cast during August: Typical climate.
Structural component: 0.25 m floor	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 14/3-1997	Signature: JXS

Temperature at casting [°C]	Density [kg/m^3]	Specific heat [kJ/kg°C]	Thermal conductivity [kJ/m·h°C]
20	2371	1.1	8

Binder content [kg/m^3]	Wind velocity [m/s]	Minimum air temperature [°C]	Maximum air temperature [°C]
357	4	15 (Soil temperature = 15)	15 (Soil temperature = 15)

Time [hours]	Insulation 1	Insulation 2	k1 [kJ/m^2·h °C]	k2 [kJ/m^2·h °C]
0	Free	Ground	75	Heat conductivity = 6
3.8	Plastic film	Ground	50	Density = 1700 kg/m^3

Inspection 1: Curing schedule (Form B5.1.5)	
File name: Hetek - Floor. Concrete A.	File No.: Example 1. Floor cast during August: Typical climate.
Structural component: 0.25 m floor	
Control plan section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 14/3-1997	Signature: JXS

Curing schedule					Initials: JXS
Hours	Maturity hours	Curing			
		Type of curing	Surface		
			Free	Form	Comments
0		Time of casting	X		
3		Plastic film		X	It must be controlled daily that the
104	94	Curing period	X		plastic film is tight and in close
					contact with the surface. The
					plastic film is kept down with sand.
					The maturity of the surface must at
					least be 94 hours before the plastic
					film can be removed.

Appendix 5.2:

Concrete wall cast during October

Planning 1: Concrete (Form B5.2.1)	
File name: Hetek - Wall. Concrete B.	File No.: Example 2. Climate: Typical of October
Structural component: 0.7 m thick wall	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 12/3-1997	Signature: JXS

Concrete composition			
Material	kg/m^3	% of binder	Comments
Cement, C			It is not required to fill in these information, as the
Fly ash, FA			wall is cast in mould, and so the requirements on
Micro silica, MS			curing are met.
FA + MS			
Binder = C+FA+MS	341		
Equiv. w/c = 0.42		Environm. class: Aggressive	

Hardening concrete			
	Q_∞, [kJ/kg binder]	τ_e, [hours]	α
Adiabatic heat development	267	15.8	1.01
Setting time, τ_0 = 4 hours			

Planning 3: Minimum period of curing (Form B5.2.2)	
File name: Hetek - Wall. Concrete B.	File No.: Example 2. Climate: Typical of October
Structural component: 0.7 m wall	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 12/3-1997	Signature: JXS

Minimum required degree of reaction R before curing can be stopped = 85 %

The corresponding maturity M is determined in one of the following three ways:

		Comments	
Calculation of $M = \tau_e/(-\ln(R))^{1/\alpha}$ =	95 hours	Calculated from: $M = 15.8/(-\ln(0.85))^{1/1.01} = 95$ hours (formula 2.3) Data have been taken from the form Planning 1 and the above-mentioned degree of reaction = 0.85.	
Or:			
M is read from a graph of the heat development:	95 hours	$Q(M) = 0.85 \cdot 267$ kJ/jg = 227 kJ/kg $\Rightarrow M \approx 95$ hours Data have been taken from the form Planning 1 and from reading the heat development graph.	
Or:			
M is taken from table 2.4:	120 hours	If the setting time $\tau_0 \leq 5$ hours	From form Planning 1
M = (M as above) + (τ_0 - 5 hours) =	hours	If the setting time $\tau_0 > 5$ hours	

Comments: The requirement on the degree of reaction before the curing can be removed has been read in table 2.3 to be 85% for aggressive
environmental class.

Planning 4: Temperature and maturity (Form B5.2.3)

File name: Hetek - Wall. Concrete B.	File No.: Example 2. Climate: Typical of October
Structural component: 0.7 m wall	
Control section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 12/3-1997	Signature: JXS

Temperature at casting [°C]	Density [kg/m^3]	Specific heat [kJ/kg°C]	Thermal conductivity [kJ/mh°C]
15 °C	2329	1.1	8.1

Binder content [kg/m^3]	Wind velocity [m/s]	Minimum air temperature [°C]	Maximum air temperature [°C]
341	5	6.1	12.1

Time [hours]	Insulation 1	Insulation 2	k1 [$kJ/m^2 \cdot h$ °C]	k2 [$kJ/m^2 \cdot h$ °C]
0	32 mm timber formwork	(As in 1)	14	(As in 1)
18	Free surface	(As in 1)	90	(As in 1)
19	Tarpaulin	(As in 1)	19	(As in 1)

Inspection 1: Curing schedule (Form B5.2.4)	
File name: Hetek - Wall	File No.: Example 2. Climate: Typical of October
Structural component: 0.7 m wall	
Control plan section:	Control plan reference:
Appendix reference:	Drawing reference:
Date: 12/3-1997	Signature: JXS

Curing schedule					Initials: JXS
Hours	Maturity hours	Curing			
		Type of curing	Surface		
			Free	Form	Comments
0		Time of casting		X	
18	Min. xx	Demoulding	X		The concrete must not be demoulded
19		Tarpaulin		X	before xx maturity hours at which
84	Min. 95	Tarpaulin is removed	X		time the requirement on the
		The top of the wall must be covered by plastic film immediately after casting			demoulding strength is met. The
					tarpaulin must not be removed until
					95 maturity hours.