Dansk Betonforening

DANISH CONCRETE ASSOCIATION

RECOMMENDATIONS FOR CURING OF CONCRETE

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CONTENTS

0. PREFACE

In 1986 the Danish Concrete Association set up a Working Committee for preparing recommedations for curing of concrete. The following persons were appointed members of the committee:

Per Fogh Jensen (chairman)
Kirsten Eriksen (from spring 1988)
Kirsten Fursund
Jacob Hougaard Hansen
Kjeld Roger Henriksen (until spring 1987)
Niels Jørgen Larsen
Knud Puckmann (until spring 1988)
Morten Tranberg (from spring 1988)
Thorkild Rasmussen (secretary)

The recommendations primarily deal with protection of concrete from drying-out, since the thermal conditions etc. are specified in Directions 125 issued by the Danish Building Research Institute.

A European enquiry has been made in connection with the preparation of these recommendations.

The recommendations concern the planning and curing of concrete in relation to the requirements made in Dansk Ingeniørforening's Code of Practice for the Structural Use of Concrete, DS 411, and the Basic Concrete Specification (BCS).

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THE DANISH CONCRETE ASSOCIATION

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1. INTRODUCTION

The present recommendations specify the present requirements for maximum loss of water of a given concrete structure in a given environment as well as the design methods available for estimating the evaporation of water from newly cast concrete surfaces. In the recommendations a survey is given of the practical possibilities for protecting a newly cast concrete surface against drying-out.

1.1 Scope

The recommendations are related to Dansk Ingeniørforening's Code of Practice for the Structural Use of Concrete, DS 411, as well as the Basic Concrete Specification, BSC, both of which are available in English.

1.2 Background

The primary condition for making a durable concrete structure is to use concrete that is properly proportioned and mixed.

Another important condition is that the casting and compaction of the concrete are carefully made so that requirements for cover, vibration etc. are complied with.

A third condition, which is, however, often neglected, is to give the concrete structure a correct curing so that it is not exposed to such adverse effects as thermal cracks, frost damage, cracks due to plastic shrinkage and general impairment of the quality due to insufficient hydrating during hardening.

2. NEEDS AND REQUIREMENTS FOR CURING

2.1 Hardening process of concrete

During the hardening process of concrete the cement reacts with water and forms a binding agent. Water is a decisive factor for the hydrating process so that the concrete may achieve the required density and strength.

The result of drying-out will be lack of hydration and thus lack of strength and density. Drying-out may furthermore give rise to cracks in the plastic and hardening concrete.

2.2 Estimation of loss of water from concrete structures

To estimate the evaporation of fresh concrete (typically 0-10 maturity hours) a method has been developed which requires knowledge of the following parameters:

- Air temperature.
- Wind velocity.
- Relative humidity of the air.
- Concrete temperature.

The calculations should be performed as shown in annex 2.

In the calculations it is assumed that the concrete surface is wet. At a certain time, however, the loss of water from the concrete will no longer be in the form of evaporation from a wet surface. Drying-out of the concrete will, however, continue. If the drying-out becomes significant the concrete will never obtain the required strength and density. Loss of water is particularly critical during the first days, dependent on the degree of hydration of the concrete. In particular it is critical for concretes with low w/c-ratios which have no surplus water. Loss of water at this time may result in cracks due to shrinkage, cf. [4] and [5]. Full hydration of the cement is achieved when the w/c-ratio exceeds 0.40, see [1].

The structure of the concrete changes through the hardening process which makes it very difficult to calculate the evaporation from hardening/hardened concrete.

In [2] a method is given for assessing the distribution of moisture and the time of drying-out. In [2] the loss of water of a number of generally used concretes under varying climatic conditions has been determined by tests. The results give an empirical design model for determining the loss of water from the concrete.

2.3 Composition of concrete

The composition of concrete is significant for the curing, i.e. when to begin the curing and the duration of it. Increased content of fine material and increased fineness of the material will reduce the bleeding on the concrete surface and make fast covering vital in order to prevent cracks due to plastic shrinkage. In BCS the content of flyash and microsilica (% of the binder) are given as control parameters for the maximum allowable time before the curing is established (cf. tables 8 and 9 in BCS).

Approximately, flyash has the same fineness as cement and it is included as a parameter due to its contribution to the quantity of fine materials and an empirically longer time of setting for concrete with flyash.

The fineness of microsilica is 50-100 times less than that of cement, and even in small quantities (5% of the quantity of cement) it may contribute to increased capillary forces and thus increased risk of cracking due to plastic shrinkage.

The quantity and fineness of cement are not included as a parameter in BCS, but high cement content will also increase the risk of cracking due to plastic shrinkage.

Addition of fibres to concrete will have a crack distributing effect, but will not prevent drying-out.

2.4 Requirements for curing

In BCS the requirement for the duration of curing formulated as a maturity requirement based on the Arrhenius-maturity function and the assumption of achievement of the following degrees of reaction (cf. specification in BCS):

- Passive environment 40% (15 maturity hours)
- Moderate environment 60% (36 maturity hours)
- Aggressive environment 90% (120 maturity hours)

Retarding effects from admixtures should be included since the duration is to be extended corresponding to the length of retardation.

The water/cement-ratio is an important factor with regard to the curing. A The ability to protect itself against drying-out will be obtained more rapidly by a strong concrete with low w/c-ratio than by a weaker concrete with a higher w/c-ratio.

In accordance with table 10 of BCS it will e.g. be possible to reduce the duration of curing from 36 to 24 hours if the w/c-ratio is reduced from 0.55 til 0.45.

The influence of puzzolans and cement types on the hardening process is not directly included as a parameter in BCS in the determination of the requirements for duration of protection against drying-out.

In most European countries the requirement for the duration of curing depends on the type of cement (rapid-hardening, normal-hardening and slow-hardening), and the type of cement is also included in the requirements of the interim Eurocode, ENV 206, cf. annex 5.

Usually, the heat of hydration is assumed to be an expression for the degree of hydration. For further information reference is made to [6].

3.0 Design

When planning a building project it is significant at an early stage to take into account the part of the work which conerns the curing.

In the choice of curing methods it is very important to evaluate the consequences with regard to time schedule and the sequence of construction. The requirement for duration of the curing may obstruct further construction for short or long periods. Protection of concrete surfaces from drying-out can e.g. be established by

- leaving the concrete in the form
- keeping surfaces wet
- covering with impermeable membranes
- spraying curing compounds on to the surface

The purpose of all methods is: to ensure and maintain an adequate moisture content in the newly cast concrete so that the required concrete quality is achieved.

3.1 Controlled climate

3.1.1 Definition

Controlled climate means control of the temperature and humidity of the air to achieve either a reduction of the evaporation or a condensation on the concrete surface. The air temperature, the concrete temperature, the relative humidity and the velocity of the wind are significant parameters for controlled climate.

In the design of the hardening of concrete knowledge of the heat of hydration of the concrete should be utilized and climatic conditions should be adjusted in such a way that an optimal hardening of the concrete structure is ensured.

The control of humidity and temperature in the curing chamber makes condensation of vapour on the concrete surface possible. This adds moisture and heat to the concrete.

Similar conditions may occur outdoors if the air temperature exceeds the concrete temperature and if the relative humidity is high. Weather changes should be closely observed so that the concrete can be protected, if necessary.

3.1.2 Execution

In the precast concrete industry controlled climate is used in curing chambers. In concrete works this is utilized by

- temperature rise in curing chamber so that the air temperature is higher than the concrete temperature,
- placing concrete in curing chambers at a high relative humidity,
- injection of vapour in curing chambers at a high temperature and a high relative humidity.

The magnitude of the vapour pressure may ensure condensation on concrete surfaces. By maintaining a relatively high humidity in a curing chamber the following can be achieved:

- When the concrete temperature is equal to the curing chamber temperature evaporation from the free concrete surface is reduced.
- When the concrete temperature is lower than the curing chamber temperature, condensation of vapour (and addition of heat) on the free concrete surface will occur.
- Since the curing process is uniform and takes place in closed curing chambers it is easy to check loss of water on test specimens.

Simple curing chambers may be plast tents over the casting site.

The diagram in [12] may be used to estimate loss of water from a fresh concrete surface immediately after grouting, see annex 2.

As seen from the diagram the vapour pressure increases significantly with increasing temperature level. Further to the vapour pressure the velocity of the wind is significant to the rate of evaporation.

3.1.3 Advantages

Surface treatment can be performed in a curing chamber.

- Simple check of loss of water (adequate control).
- Uniform hardening process.
- No special precautions prior to surface treatment, if any.

3.1.4 Drawbacks

- Requirements for control.
- Specific design of production area.
- Increased maintainance of forming equipment etc. due to moisture.
- Working environment in curing chamber.

3.1.5 Quality control

- Calculation and planning of process.
- Verification (loss of weight) on test specimens.
- Check of key parameters (air temperature, concrete temperature, wind velocity, relative humidity, maturity).

3.2 Form materials

3.2.1 Definition

Requirements for protection against drying-out are only made for free concrete surfaces, since concrete surfaces towards the form are assumed to be protected from drying-out.

Water-proof, non-absorbent form materials which give good protection against drying-out are e.g.

- Varnished timber/plywood.

- Oiled plywood or melamine coated plywood.
- Steel.
- Varnished concrete.
- Water-saturated concrete in construction joints.

3.2.2 Execution

The form system should be impermeable and non-absorbent to give the best protection against drying-out. Such form system should be chosen that thermal cracking and freezing are avoided and so that maturity requirements are satisfied prior to striking of formwork. The insulating properties of the form material and its significance to the maturity development of the concrete should be taken into account.

In the case of untreated timber formwork the actual moisture condition of the timber will be significant. Measures should be taken to ensure that the timber is water saturated, e.g. by watering prior to casting. Fresh timber will retain this moisture for a considerably longer period than in cases where the timber has been dried and watered again by repeated use.

3.2.3 Advantages

- Impermeable and non-absorbent form gives good protection against drying-out.
- No special precautions prior to surface treatment, if any.

3.2.4 Drawbacks

- Absorbent and leaking formwork causes loss of water.
- Formwork to comply with the requirements for drying-out protection might be expensive.
- Special precautions to be taken at construction joints.
- In the case of long striking time the formwork may adhere to the concrete.

3.2.5 Quality control

- Calculation and planning of process.
- Check of the condition of the formwork.
- Recording of maturity development in the structure.
- Check that the time for which the formwork remains fulfils the maturity requirement.

3.3 Watering

3.3.1 Definition

Water film on the surface protects the concrete against drying-out. It will only in special cases be possible to use water curing of newly cast concrete, and protection during the first period should be otherwise ensured.

When the concrete has obtained a certain hardening (10 - 15 maturity hours) the concrete surfaces will, however, be able to sustain the contact with water without being washed out.

3.3.2 Execution
Water can be added to the concrete in different ways which should be chosen in accordance with the actual needs and possibilities:

- Watering.
- Water curing.

Precautions should be made to prevent too large temperature differences in the structure.

Watering
Sprinkling should be used for keeping construction joints, precast products, etc. moist. The method is particularly used in the manufacture of concrete products.

Drawbacks for other building sections should be estimated before commencement of watering.

Water curing
The method is used in the production of certain special elements in the precast concrete industry, and it is not commonly used since requirements for basin dimensions give certain limitations.

3.3.3 Advantages

- Water can be added to the concrete in different ways.
- Certainty that the surfaces that are watered are constantly moist, which ensures favourable hydration of the concrete.
- No special precautions prior to surface treatment, if any.

3.3.4 Drawbacks

- Risk of plastic shrinkage due to late commencement.
- Risk of thermal cracks.
- Blemishes and discolouring of surface.
- Risk of freezing.
- Surveillance of functioning of watering system (week-ends).
- Washing out of fresh concrete.
- Unsuitable on the bottom of concrete decks.
- Slow maturity development in the surface.

3.3.5 Quality control

- Calculation and planning of process.
- Even and constant watering.

- Calculation of maturity before watering is discontinued.

3.4 Wet sacks

3.4.1 Definition

The surface of the concrete is to be kept moist by covering with water saturated material.

3.4.2 Execution

Soaked jute fabric (sacks) or felt mats are to be applied/suspended.

The cover is to be kept moist either by frequent sprinkling or by constant addition of water, e.g. using perforated hoses.

In order to avoid thermal cracks due to cooling this method can be combined with foil or tarpaulin covering. When moist materials are used for covering without addition of water the materials should also be protected from evaporation with plast foil or similar and the moisture of the covering material should be controlled until the concrete har obtained the required maturity. Under adverse conditions jute and similar material that are drying-out might increase the evaporation from the fresh concrete, and thus impair the conditions.

The need for combined protection of moisture and protection against loss of heat has given rise to the development of plast coated felt mats which combine effective moisture protection with protection against cooling. When felt mats are used the tendency for condensation blemishes is reduced. The method is used to a limited extent on the building site.

3.4.3 Advantages

- It is possible to protect vertical as well as horizontal surfaces.
- Flexibility in relation to construction of adjacent structures.
- Construction joints can be protected from drying-out.
- No special measures to be taken before surface treatment, if any.
- Working environment.

3.4.4 Drawbacks

- Imprinting in fresh concrete surfaces.
- Week-end inspections.
- Risk of freezing of water saturated surfaces.
- Washing out of fresh concrete.
- Not suitable for the bottom of concrete decks.
- Risk of blemishes and discolouring.

3.4.5 Quality control

- Calculation and planning of process.
- The entire, free surface should be covered with sacks/felt mats.
- The cover should be kept wet.

- Covering should be established in time and should be maintained until the required maturity is reached.
- Possible to control the effectivity of the wet state and of any cooling.

3.5 Plast foils, insulation mats and tarpaulins

3.5.1 Definition Evaporation from the concrete surface can be prevented/reduced by covering it with plast foil, insulation mats or damp proof tarpaulins.

3.5.2 Execution

Plast covers should have a tight fit to the surface, and they may efficiently prevent evaporation. It requires, however, that the design of the structure is regular without re-entrant corners and that the concrete surface is not broken by reinforcement etc. Thus, such cover cannot normally be used in construction joints. A tight fit of the foil/tarpaulin to the concrete should be ensured so that wind channels are avoided. Also laps of at least 20-30 cm should be ensured. Precautions should be taken at edges and laps in particular to ensure that the cover is not blown off by the wind. The plast foil should be flexible and strong. It is possible to use tarpaulins several times and due to their weight a tight fit to the concrete is easily established.

Mats of foam plast/winter mats are insulating mats which also contribute to the insulation of the structure. If the mats have a non-porous structure preventing water transport or if they are wrapped in plast they may as well be used for protection against drying-out.

The method is applicable at building sites as well as in precast industry.

3.5.3 Advantages

- Flexbile method in relation to execution of adjacent structures.
- Re-use of tarpaulins and insulation mats.
- No drawbacks for subsequent surface treatment.
- Minimum of maintenance.
- Less risk of imprinting of plast foil in the fresh concrete.
- Environment of work.

3.5.4 Drawbacks

- Not suitable at the bottom of decks.
- Risk of condensation blemishes.
- Wind tunnels.
- Imprinting in fresh concrete (tarpaulins).

3.5.5 Quality control

- Calculation and planning of process.
- The cover should have a tight fit to the surface and should be fixed everywhere.
- Laps should be at least 20-30 cm.

- Covering should be placed in due time and should be maintained until the required maturity has been achieved.
- The covering should be intact.

3.6 Curing compounds

3.6.1 Definition

Evaporation can be reduced by applying a curing compound to the concrete surface.

A curing compound is a liquid in which organic compounds are dissolved or emulsified. Such compounds are able to form a protective membrane on the concrete surface.

Generally, a distinction is made between using water or an organic solvent (xylene, alcohol, terpentine or similiar). The type of liquid should be specified in the MAL-code of the user's guidance which should also specify the precautions to be taken in connection with the safety of work.

In the case of water-based products the active components (forming a film) are usually emulsins of wax, polyglycol, acryl, etc. while, in the case of solvent-based products the components may be chlorinated rubber, resin, acrylate etc. The sealing effect is established by evaporation of the water/solvent. Then the active components form a coherent membrane whose impermeability is significant to the effect.

In BCS requirements for the efficiency of these curing compounds are specified, since they should be able to reduce the loss of water by at least 75% in relation to the loss from an untreated surface in accordance with the test method TI-B 21 [8].

3.6.2 Execution

Curing compounds are primarily used to protect fresh concrete. However, they can also be used after striking of formwork. The sealers are applied as a uniform coat by spraying on to the fresh concrete surface when it is in a dull, dry state. The efficiency of curing compounds when applied to hardened concrete is uncertain, but in accordance with [10] efficiencies of 15-30% have been obtained.

If the curing compound is applied by spraying the specifications of the manufacturer with regard to quantities to be used, spraying equipment, temperature conditions etc. should be complied with. If the concrete surfaces are uneven or broomed it should be taken into account that the surface area may be up to 30% larger than the theoretical "flat" area. Furthermore, the curing compound may accumulate in cavities.

Experience has shown that it is difficult to apply the required quantities to vertical surfaces, and several applications may be necessary.

Due to environmental precaution water-based products are preferable. Often water-based wax emulsins give an efficiency in the range of 70-90%, however, they are not easily removable.

Several solvent-based products provide high effectivity, 80-90%, and in several cases they are more easily removed prior to surface treatment, if any. Compliance with the environmental requirements is significant.

Volatile dyers have been added to many sealers for visual ensurance against "holidays".

The method is used on the building site as well as in the precast concrete industry. The method is particularly applicable to slipform construction.

Sealers are not applicable in cases where subsequent casting or surface treatment is to be carried out.

3.6.3 Advantages

- Low-cost method.
- No drawbacks for construction of adjacent structures.
- Simple method of work - no maintenance.

3.6.4 Drawbacks

- Inefficient control of the quantity used.
- Use of curing compound gives rise to drawbacks in the case of surface treatment and adhesion problems in construction joints.
- Problem to apply curing compound in due time in the case of large floors.
- Aesthetical problems.
- Dubious efficiency on stripped (hardened) concrete.
- Application of curing compound requires +°C.
- Surface should be completely finished prior to application of curing compound.
- Uneven application when subjected to wind.
- Risk of problems in connection with the environment of work.

3.6.5 Quality control

- Efficiency to be documented (documentation and/or trial casting).
- No "holidays" (visual inspection of change of colour).
- Control by weight of average consumption.
- Inspection of spraying equipment.

3.7 Other methods

3.7.1 Polymers

Polymers are used increasingly as admixture to concrete. Since, to a certain extent, these materials can be compared with e.g. curing compounds the thought of making the concrete self-curing by addition of polymers is obvious. Whether or not this is possible, however, has not been clarified so far.

3.7.2 No constructive protection - utilization of BCS

Unless otherwise proved to be sound, protection against drying-out should be established before a quantity of water as specified in BCS table 8 has evaporated from the surface.

These quantities correspond to a concrete depth greater than or equal to 0.2 m. For depths less than 0.2 m the quantities of water should be reduced in proportion to the depth.

Temporary protection should be established to the necessary extent prior to screeding. If documentation of the loss of water is not available the concrete should be protected against drying-out as specified in BCS table 9. Reference is also made to the example in annex 2.

Even if the above rules are complied with, drawbacks can arise in connection with treatment of the surface. As an example, it may be difficult to finish a surface of concrete with a low w/c-ratio when the surface has dried-out while the concrete below is workable/flexible.

The requirements for loss of water may be complied with, but the degree of drying-out of the surface exceeds that of the concrete below the surface. Such conditions call for stricter requirements for careful curing.

3.7.3 Vacuum compaction

The method is not only a method of curing, it can also be used for further treatment of the concrete, see [9]. Vacuum compaction is used for removing surplus water and it is the purpose to reduce the w/c-ratio or to remove the bleeding water from the fresh concrete surface in order that protection against drying-out and treatment of the surface may be established sooner. The quantity of water removed from the fresh concrete by vacuum compaction should not be included in the quantities of water specified in table 8 of BCS.

Vacuum compaction will squeeze the water out of the concrete. A vacuum is applied to the concrete through a filter on the concrete surface. Vacuum compaction can change the air void structure of the concrete.

The method is carried out in fields on the free surface, and the fields should overlap in an appropriate manner.

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ANNEX 1

Example from the design phase

In BCS and ENV requirements are given for the duration of protection against drying-out. The basis for the requirement of BCS is a number of maturity hours corresponding to the degree of reaction. For the environments, 15 maturity hours (passive environment) correspond to a degree of reaction of 40%, 36 maturity hours correspond to a degree of reaction of 60% and 120 maturity hours (aggressive environment) correspond to a degree of reaction of 90%.

From figure 1.1 it can be seen that degrees of reaction of 90%, 60% and 40% for ordinary hardening Portland cement correspond approximately to maturities of 120, 36 and 15 hours, respectively.

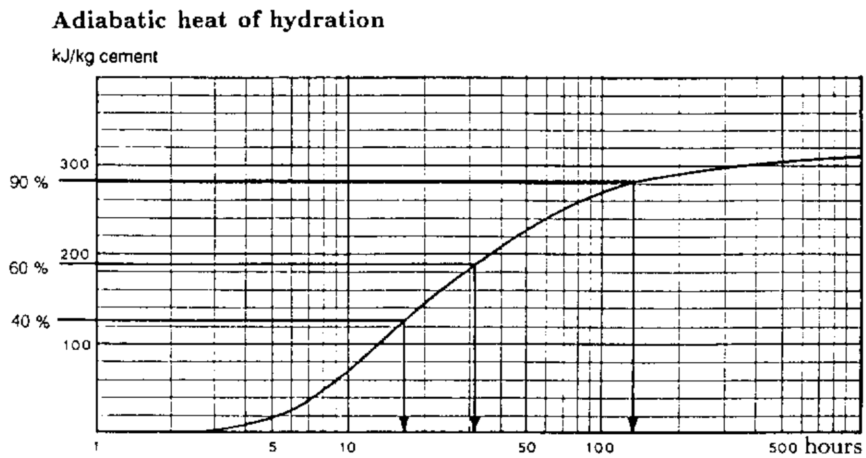


Figure 1.1 Heat of hydration for concrete with PC(A/HS/EA/G), (normal-hardening Portland cement).

The determination of the heat of hydration of an actual concrete mix by adiabatic calorimetry can often be utilized for a reduction of the requirement for the duration of protection against drying-out when the degree of reaction is compared with environmental conditions and the actual heat of hydration.

Example:
Normally, it is assumed that facades are used in moderate environments, but this example deals with facades which are exposed to sea fog and frost. Therefore, aggressive environmental class is prescribed.

For concrete sandwich facades to be used in extremely aggressive environment, protection against drying-out is required in accordance with the requirements of BCS for aggressive environmental class, i.e. for 120 maturity hours or until a degree of reaction of 90% has been achieved.

It is not possible, when using a normal casting cycle of 24 hour hardening time in the form, to comply with the requirement for keeping up the protection against drying-out for 120 maturity hours. Extraordinary measures after striking of formwork will be required.

From figure figure 1.2, which shows determination of the heat of hydration of a concrete with a rapid-hardening Portland cement, it is seen that a degree of reaction of 90% has been reached after 48 maturity hours.

Adiabatic heat of hydration

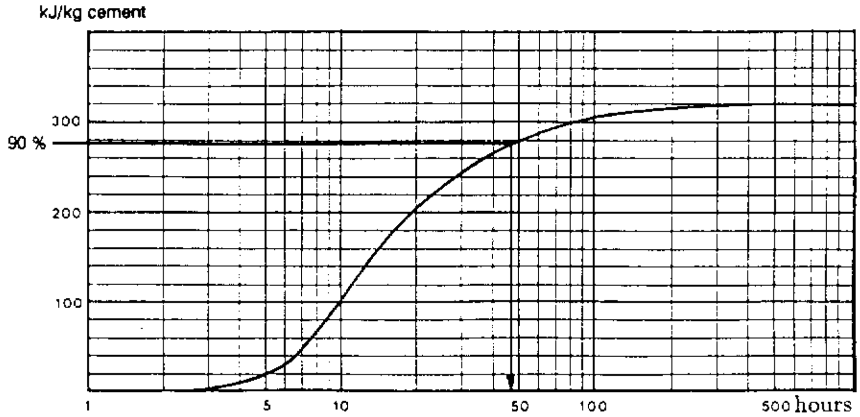


Figure 1.2. Heat of hydration for concrete with PC(R/IS/MA/G).

Calculation of the curing cycle to achieve 48 maturity hours prior to striking of formwork and compliance with requirements for temperature difference can be seen from figures 1.3 and 1.4 where the hardening time in form is 18 hours.

From figures 1.3 and 1.4 it can also be seen that approximately 50 maturity hours can be assumed after 18 hours of hardening when using a casting temperature of 35°C, while a casting temperature of 30°C will result in approximately 42 maturity hours.

Thus it is possible to comply with the requirements of BCS for duration of protection against drying-out within a 24 hour casting cycle, since a degree of reaction of 90% is fulfilled after 48 maturity hours. No further measures are necessary.

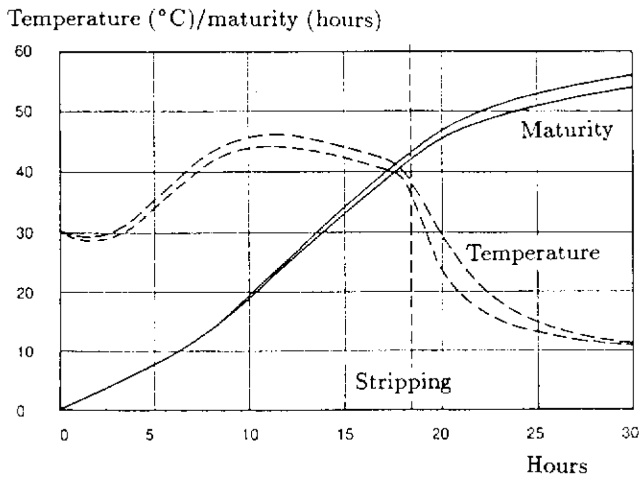


Figure 1.3.
Simulation of temperature and maturity development. Casting temperature 30°C.

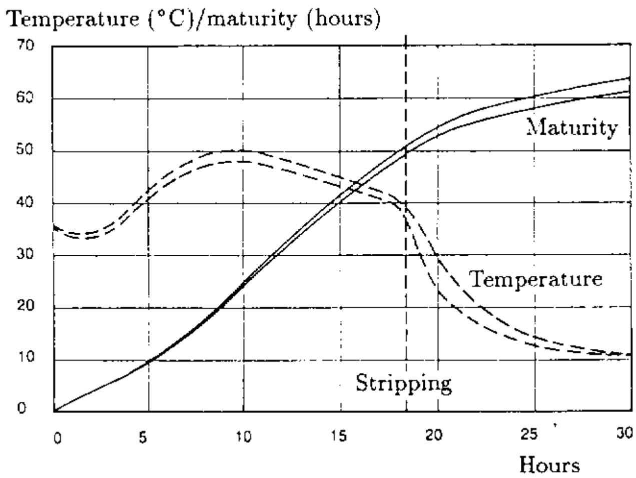


Figure 1.4.
Simulation of temperature and maturity development. Casting temperature 35°C.

Subsequent control of the curing process shown in figure 1.5 shows that a maturity of approximately 54 hours can be achieved after 18 hours of hardening and at a casting temperature of approximately 35°C. Thus, the calculation complies with the actual hardening process.

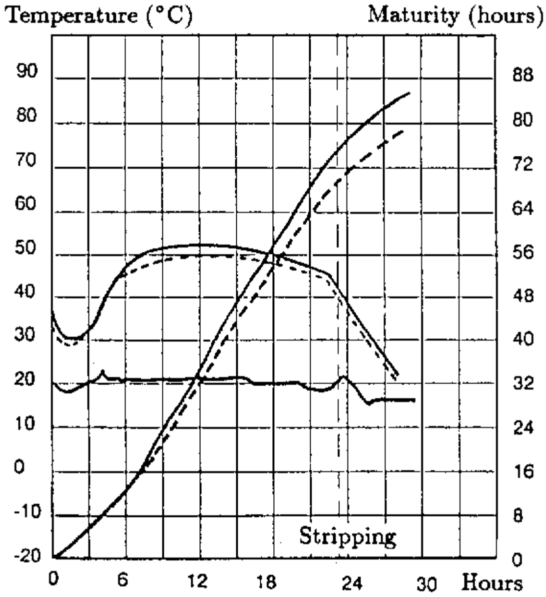


Figure 1.5. Measured temperature and maturity development. Casting temperature 35°C.

ANNEX 2

Example of utilization of BCS, table 8

The nomogram shown below can be used for assessment of the evaporation from a wet concrete surface. When the temperature of air and concrete and the relative humidity is known it is possible to calculate the rate of evaporation from the wet concrete surface.

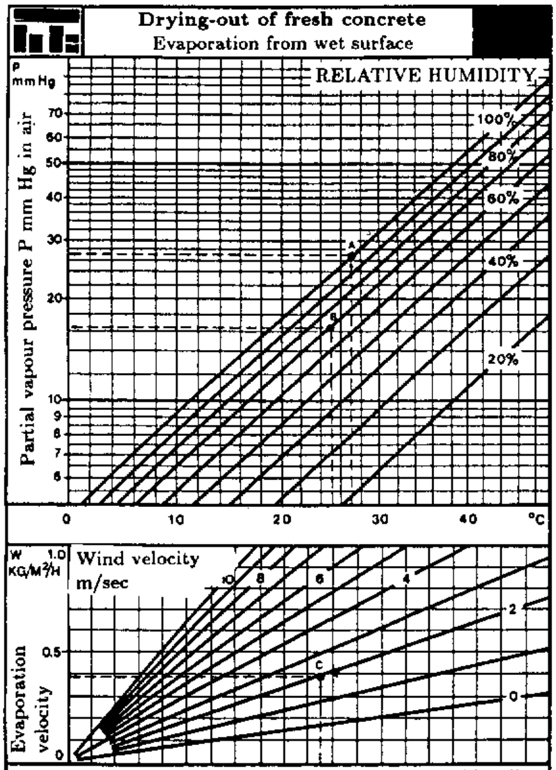
Example:

A newly cast outdoor concrete structure with a thickness of 200 mm, with a wet surface and a temperature of 27°C, air temperature of 25°C, relative humidity of 70°C and wind velocity of 2 m/sec is considered. A relative humidity of 100% at the concrete surface is assumed.

The vapour pressure at the concrete surface is in the top nomogran specified as 27 mm Hg and the vapour pressure of the air is 16.5 mm Hg.

Thus, the difference in the vapour pressure is 27 - 16.5 = 10.5 mm Hg.

In the bottom nomogram a rate of evaporation of about 0.4 kg water/hour m^2 for a vapour pressure of 10.5 mm Hg and a wind velocity of 2 m/sec is specified. Reference is also made to section 3.1 - controlled climate.



Evaporation velocity as a function of wind velocity and vapour pressure potential is calculated from

$\dot{W} = (0.015 + 0.011 \cdot v)\Delta P$ in kg/m^2 h

Requirement: Wet surface until maturity 10-20 hours

Figure 2.1. Nomogram for assessment of evaporation of water from a wet concrete surface. The nomogram is made by Beton- og Konstruktionsinstituttet (The Concrete and Structural Research Institute).

Using the above information the requirements in BCS table 8 can be converted to equivalent time requirements. Thus, in this case a loss of water of say 3 kg/m^2 will correspond to approximately 7.5 hours.

ANNEX 3

Example of evaporation/condensation

Industrial production of concrete is often performed using curing chambers at a high temperature and a high relative humidity. If the temperature of the concrete is below the saturation point temperature of the air, condensation on the concrete surface will take place. The condensation has the effect that moisture and heat are added to the concrete.

Later in the curing process also the heat of hydration of the cement will contribute to heating of the concrete, and at a certain time the concrete temperature exceeds the saturation point temperature of the air. Therefore, evaporation from the concrete surface will take place instead. Contrary to condensation the evaporation has the effect that energy is removed from the concrete, and therefore the evaporation will have a cooling effect on the concrete.

The nomogram shown in figure 2.1 in annex 2 can be used for estimation of these conditions.

In the following a concrete panel cast at 20°C is considered. The panel is not covered and is placed in a curing chamber at 30°C and 90% relative humidity.

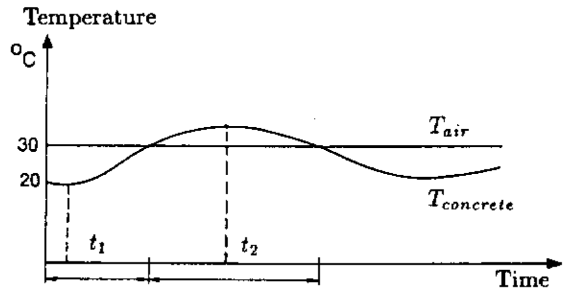


Figure 3.1. Principal temperature development in curing chamber.

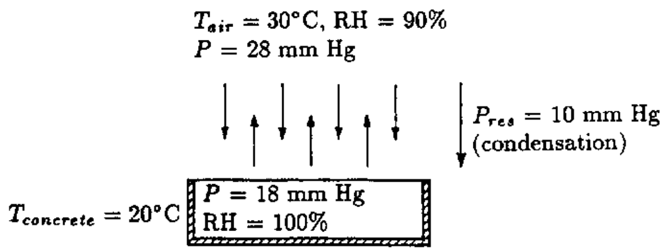


Figure 3.2.
Vapour pressure at the time t_1, cf. figure 3.1

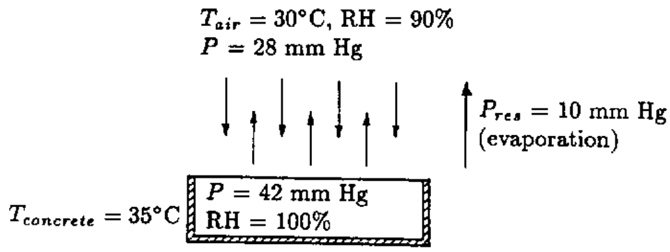


Figure 3.3.
Vapour pressure at the time t_2, cf. figure 3.1.

Figure 3.1 shows the temperature development under curing.

Figure 3.2 shows that initially there will be a resulting difference in vapour pressure down towards the concrete surface, resulting in condensation of water on the concrete surface, which will then be heated.

Similarly, from figure 3.3 it is seen that at a later time the vapour pressure will be diverted from the surface resulting in evaporation from the concrete surface and thus cooling.

Since the concrete temperature will vary the nomogram cannot directly be used to analyse the conditions. The method described in [2] allows for combined transport of moisture and heat.

Documentation can be obtained by control weighing of test specimens that are placed in the curing chamber.

Example of considerations regarding curing

An assessment of the protection against loss of moisture is required for the casting of a 40 cm thick wall. The contractor wants to strike the formwork after 24 hours due to re-use of the form.

The requirements are:

Environments: Moderate
w/c-ratio: 0.52
Casting temperature: 12°C
Air temperature: 10°C

Cement content: 290 kg Rapid-hardening Portland cement/m^3 concrete
Form material: 19 mm plywood
Wind velocity: 5 m/sec

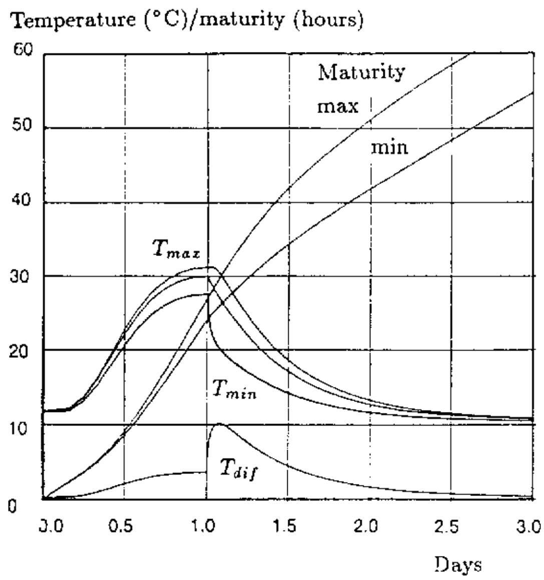


Figure 4.1
Simulation of temperature development and maturity development.
Casting temperature 12°C,
non-insulated form.

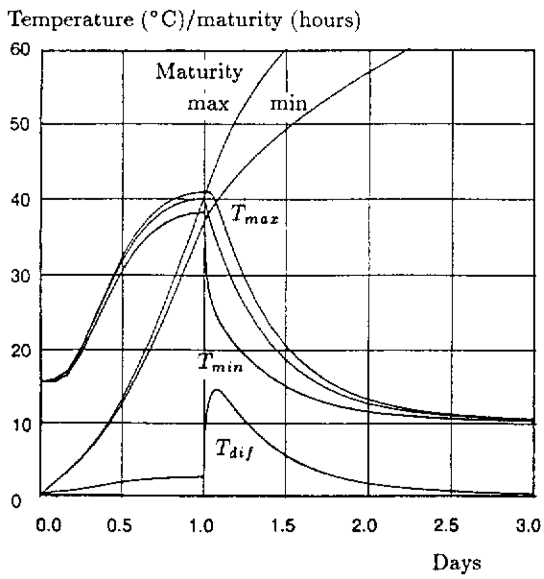


Figure 4.2
Simulation of temperature development and maturity development.
Casting temperature 16°C,
insulated form.

In accordance with table 10 of BCS the earlist time of removal of protection against drying-out will be 36 maturity hours. A previous temperature simulation has indicated an expected process as shown in figure 4.1. It is seen from the figure that the maturity of the surface after 24 hours will be approximately 20 maturity hours.

The conctractor may choose between several alternatives to ensure compliance with the 36 hour maturity requirement.

Alternative 1
The contractor may choose to re-cover the concrete with tarpaulins etc. after striking.
Alternative 2

The conctrator may choose to invest in an extra form and to extend the striking time to 48 hours.

Alternative 3
The contractor may choose a concrete with a w/c-ratio equal to 0.45. Thus, the maturity requirement is reduced to 24 hours, cf. BCS, which will be obtained after 24 hours.

Alternative 4
The contractor may e.g. perform extra insulation of the form using 10 mm polystyrene sheets and he may use a concrete with a casting temperature of 16°C. Thus, it will be possible to obtain 36 maturity hours within 24 hours, cf. figure 4.2.

The final choice will be based on a total estimate of the economy and the practical/technical advantages and disadvantages involved.

ANNEX 5

Requirements of the European code

The interim European code, ENV 206, which is expected to form the basis of a common European code, reflects the rules in the countries where requirements for curing already exist.

ENV 206 prescribes that the curing should be established "as quickly as possible". This formulation is not unambiguous, since the "possible" will be based on a subjective estimate.

However, under certain conditions, compliance with the requirements of BCS will involve practical problems.

Furthermore, ENV 206 deals with the same methods of curing as those known in Denmark, and the requirements with regard to duration are specified in table 5.1. Alternatively, however, the duration can be based on an assessment of maturity and degree of hydration in the actual situation or in accordance with local requirements. Thus, it is still possible to use national requirements. Table 5.1 applies to use in moderate environments, and for aggressive environments it is merely stated that the times should be "considerably" increased.

In table 5.1 a parameter is introduced describing the strength development of the concrete as rapid, medium or slow. This parameter depends on the w/c-ratio and on the type of cement. Furthermore, in ENV 206 classification of the climatic conditions during curing has been introduced. This grading takes due account of wind, humidity and sun exposure.

Indirectly, BCS takes these conditions into account with regard to duration of the curing.

The maturity is not directly included in table 5.1 since it has been chosen to use the concrete temperature as a parameter instead.

One of the reasons why the maturity concept has not been introduced into table 5.1 probably is that different maturity constants are used in the respective countries.

	Strength development of concrete								
	Rapid			Medium			Slow		
Concrete mean temperature / Ambient conditions during hardening	5	10	15	5	10	15	5	10	15
No direct sunshine, relative humidity of surrounding air not lower than 80%	2	2	1	3	3	2	3	3	2
Medium sunshine or medium wind or relative humidity not lower than 50%	4	3	2	6	4	3	8	5	4
Bright sunshine or strong wind or relative humidity below 50%	4	3	2	8	6	5	10	8	5

Table 5.1. Requirements for duration of protection against drying-out in accordance with ENV 206, [5].

Determination of the strength development of the concrete in accordance with ENV 206 is specified in table 5.2. The cement notation corresponds to the European code EN 197, March 1987 edition. The Danish types of cement, Rapid-Hardening Portland Cement, Portland Flyash Cement, Low-Alkali Sulphate-Resistant Cement and White Portland Cement are all assigned to strength class 42.5 R.

The requirements of ENV 206 and BCS as well as other requirements made in connection with curing reflect the efforts of formulating operational requirements within a very complicated area.

Rate of strength development	w/c-ratio	Strength class
Rapid	< 0,5	CE I 42.5 R
Medium	0,5-0,6	CE I 42.5 R
	< 0,5	CE I 42.5; CE II 32.5 R CE II-IV 42.5 R
Slow	All other cases	

Table 5.2. Characterization of the strength development of concrete in accordance with ENV 206. The cement notation corresponds to EN 197, [5].