HETEK

Curing
State of the Art

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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 where part no 6 concerns Curing.

The State of the Art regarding evaporation protection, curing methods and their influence on the concrete surface quality is described. Further, relevant test methods used to evaluate the concrete surface quality and the existing models to describe the correlation between curing method and surface quality are presented.

Based on a survey of the existing relevant literature and earlier performed tests it can be concluded that a number of tests have been performed world wide to evaluate different curing methods and their influence on the concrete surface quality and a lot of different test methods have been used to describe the obtained quality.

Most of the performed tests have been based on the principle: test and observe without modelling of a theory in advance. This is probably caused by the fact that only a limited number of models exist to describe the correlation between the curing method and the obtained surface quality.

Finally, the needed research regarding curing methods and surface quality is proposed.

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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 excess of 100 years in an aggressive environment.

The research programme includes investigations regarding the conctractor'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 eight parts within the following subjects:

- chloride penetration
- frost resistance
- autogenous shrinkage
- 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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and

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The purpose of the project is to investigate the effect of different curing methods on the quality of the concrete surface and to prepare a guideline regarding curing.

Curing method is defined as the combination of the type of surface protection and the protection period.

The results of the project will be 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 Criterias
HETEK - Curing - Main Report
HETEK - Curing - Guideline.

In this report chapter **3. Contractors' Curing Experience in Denmark** gives a short summary of the methods used in practise for protection of young concrete against evaporation. The chapter is written by the contractors representatives in this project and can therefore be evaluated as the State of the Art seen from practise including the contractors wishes to the development of new technology - which is indeed the purpose of the HETEK-project.

March 1996

Per Fogh Jensen
Anette Berrig
Steering Committee of the HETEK-Curing project

1. Introduction

In this report a State of the Art regarding evaporation protection, curing methods and their influence on the concrete surface quality will be described. Further, relevant test methods used to evaluate the concrete surface quality and the existing models to describe the correlation between curing method and surface quality will be presented.

The State of the Art is based on a survey of the existing relevant literature and earlier performed tests.

2. Background

In order to obtain a good quality of the concrete surface layer the contractor shall protect the surface of the concrete against damaging drying out. A high quality of the concrete surface layer is required by the owner because the surface layer shall ensure a long durability of the concrete structure by protecting the reinforcement against corrosion. This requires protection of the fresh concrete as well as protection of hardening concrete during the first time of the hardening period.

If the concrete has not been protected properly damaging drying out of the concrete surface can occur. The consequence can be cracks and increased porosity of the surface. The crack formation and increased porosity will reduce the strength and waterproofness and increase the risk of reinforcement corrosion caused by chloride migration and carbonation. This will reduce the durability of the concrete.

In practise these damages caused by drying out have been avoided by reducing the evaporation from the concrete. Reduced evaporation will prevent plastic shrinkage cracks, and ensure that the water in the concrete is present to create a dense concrete surface based on the reaction between the cement and the water.

In concrete specifications for construction projects - such as the "Basisbetonbeskrivelse" (BBB) [ATV-udvalget vedr. betonbygværkers holdbarhed, 1987] and the "Almindelig arbejdsbeskrivelse" (AAB) [Vejregeludvalget, 1994] - requirements regarding curing are stated to ensure a good concrete quality of especially the concrete surface layer. These requirements are formulated as triple requirements because they state:

- how early
- how efficient and
- how long

the concrete surface shall be protected against evaporation.

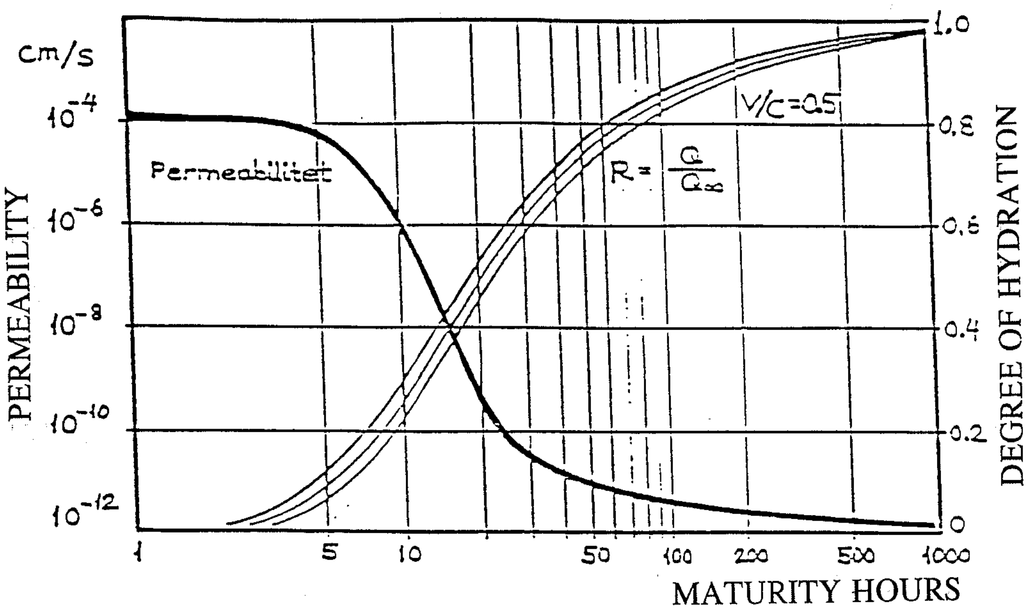
The requirements in the BBB and the AAB are based on the assumptions described in the explanatory document to the BBB [ATV-udvalget vedr. bygværkers holdbarhed, 1986] which was prepared in connection with the preparation of the BBB.

In the explanatory document to BBB it is described that the required maximum amount of water allowed to evaporate before protection is established is based on practical experience to avoid plastic shrinkage cracking.

The required protection period for concrete in an aggressive environment is based on the assumption that it shall be possible to obtain a relative degree of hydration of the cement of at least 90 %. With a degree of hydration of 90 % the concrete is assumed to be dense with small pores. This assumption is based on the correlation between the concrete permeability, the maturity and the degree of hydration as shown in figure 2.1.

The relative degree of hydration is stipulated from the adiabatic heat development. 90% is fixed as the point where 90% of the heat development (Q_∞) tested according to NT BUILD 388 is reached. According to figure 2.1 it is reached after approximately 200 maturity hours.

Figure 2.1: Correlation between the concrete permeability, the maturity and the degree of hydration [ATV-udvalget vedr. betonbygværkers holdbarhed, 1986]



In the BBB it is required that for concrete in an aggressive environment the protection shall be established before a certain amount of water has evaporated from the surface. This amount of water varies between 1.5 kg/m^2 and 6.0 kg/m^2 depending on the amount of fly ash and silica fume in the concrete. In case of high amounts of fly ash and silica fume the requirement is 1.5 kg/m^2. These quantities of water correspond to concrete layers thicker than or equal to 0.2 m. If the layer thickness is less than 0.2 m, the quantities of water should be reduced in proportion to the thickness. The protection shall be established before the above mentioned quantities of water has evaporated from the surface, yet not later than one hour after setting time.

Further, the concrete structures shall be protected against evaporation for a period of at least 120 maturity hours if the w/c-ratio is between 0.45 and 0.40. If the w/c-ratio is below 0.40 the protection period may be reduced to 96 maturity hours.

The use of curing compounds is allowed if the effect of the curing compound is higher than 75 %. The efficiency shall be tested according to the test method TI-B 33 [TI-B

33, 1992]. The test method is a Danish developed method and is remarkable because it tests the efficiency of the curing compound with a stabil wind velocity at 3.6 m/s.

In the AAB it is required that protection of the concrete surface irrespective of the amount of fly ash and silica fume shall be established before 1.5 kg/m^2 of water has evaporated from the surface.

However, AAB's requirements regarding protection period are more strict than the requirements of the BBB because BBB is for houses and the AAB is for bridges.

For structures in an aggressive environment AAB requires that the surface shall be protected for at least 120 maturity hours. This protection period is prolonged to 180 maturity hours for structures in the most aggressive environment.

For bridge structures such as Storebælt and Øresund the required amount of evaporated water before protection shall be established is reduced to 0.5 kg/m^2.

The stated requirements to maximum amount of water allowed to evaporate before protection is established are often difficult for the contractor to fulfil. This is caused by the required surface finish of the concrete such as trowelling combined with the prize-optimized 3-powder concrete types.

The contractor is therefore interested in more information about to what extent the concrete surface quality depends on the amount of evaporated water from the fresh concrete and whether it is possible to allow a higher amount of water to evaporate without damaging the surface quality.

The requirements to the length of protection periods have been increased during the last ten years. This means that the protection period gets longer. The contractor's work is slowed down and his possibility of re-using the protection materials has therefore been reduced which makes the construction more expensive.

Further, some investigations performed by DTI and Dansk Beton Teknik A/S for the Great Belt Contractors [Lundberg, 1994] have indicated that a shorter period with formwork on the concrete surface combined with use of curing compound can result in a higher concrete quality measured as number of micro cracks compared with concrete protected with formwork for a long period. More details about these results are given in chapter 6.1.

It would therefore be desirable to acquire more information about how long the protection period needs to be and how effective the protection needs to be to obtain a concrete surface of high quality.

If it is possible to rank the curing methods as a function of obtained concrete surface quality, it might be possible to use this information for revision of the existing requirements to the latest protection moment, the protection efficiency and the protection period.

3. Contractors' Curing Experience in Denmark

This chapter contains a summary of evaporation protection methods of concrete structures used by contractors in Denmark.

On the basis of project requirements and concrete composition and with a view to the planned execution of the casting the contractor stipulates the curing methods. The methods chosen must comply with the project specifications and at the same time result in best possible execution of the concrete work. The survey below shows the methods most frequently used, and the figures to the right refer to the list of reference projects in figure 3.1, and state the projects where the methods have been applied.

	Ref. to figure 3.1
Membranes	
- plastic foils	1,2,3,4,5,6
- tarpaulins	3,6
- Ethafoam mats	3,6
- winter mats	1,3,6
Sealing of the Surface	
- curing compounds	5,1,6
Climatic Conditions	
- water curing	
- air humidity	4,6
- protection from wind/solar radiation	4
- curing chamber	6
Form	
- prolonged form period, so that the requirements concerning evaporation protection are met in the form	1,2,3
- optimum form period which gives a better utilization of the form in combination with other evaporation protective methods.	

Figure 3.1: List of reference projects.

No	Project	Reference
1	The Alsund Bridge	[Vejdirektoratet, 1983]
2	The Farø Bridges	[Gotfredsen, 1985]
3	The Guldborgsund Tunnel	[Monrad, 1990]
4	The ryå Bridge	[Vejdirektoratet, 1983]
5	The Madum Å Bridge	[Vejdirektoratet, 1985]
6	The Great Belt Link West Bridge, East Tunnel and East Bridge	Contractor's experience 1988-1995

3.1 Membranes

Free concrete surfaces and stripped concrete surfaces can be covered with membranes to protect against evaporation. The best result is obtained when the surfaces to be protected are regular and plane, and where gravity due to the design of the structure keeps the membrane close to the concrete surface.

All types of membranes must be laid with overlapping and must be maintained to meet the objective.

Free Surfaces

Membranes for protection against evaporation of free concrete surfaces will in practise not be applied until the contractor has worked the surface to the specified finish. It is not appropriate to apply/ remove/apply etc. the membranes until the surface finish has been performed according to the project requirements. The surface as well as the membranes would be ruined by such procedure, and the heavier the membrane, the greater the requirement has to be to the bearing capacity of the concrete before the membrane is applied. Wind action can in addition complicate the temporarely protection.

Thus the use of membranes placed directly on surfaces is often based on compromises in relation to time of initiation and evaporation protection:

- the membrane is applied when surface finish is completed which can be later than prescribed
- another composition of concrete is chosen which makes it possible to execute surface finish and meet the requirements concerning evaporation protection
- the execution method is revised by creation of shelter/increased air humidity/lower conccrete temperatures, etc).

Stripped Surfaces
Tarpaulins are often chosen for stripped vertical surfaces due to their weight and durability. Ethafoam (trade name for plastic foam approx. 2 cm thickness) mats are also used, e.g. to cover wide columns, as the mats that are available in "endless" lengths can be wrapped tightly around the structure.

However, it is generally problematic to cover vertical surfaces, especially when working in great heights.

Insulation Mats
In order to meet the requirements concerning curing temperature and at the same time provide protection against evaporation it may be necessary to use insulation mats, and the requirements concerning insulation effect determine the type of mats.

On horizontal surfaces Ethafoam or winter mats are used, the Ethafoam mats are handier and considerably more durable. For pedestion areas the Ethafoam mats are preferred as the winter mats have a slippery surface and are easily damaged when exposed to traffic.

Due to their weight winter mats will adhere better to vertical structures, but the mats are complicated to handle and maintain. The Ethafoam mats are easier to wrap around the structure, and the necessary overlapping is easily achieved.

3.2 Sealing of the Surface (Curing Compounds)

Curing compounds provide the contractor with some obvious advantages in the protection against evaporation of concrete, but curing compounds shall have a minimum efficiency according to BBB [ATV-udvalget vedr. betonbygværkers holdbarhed, 1987] and AAB [Vejregeludvalget, 1994]. The supplier's instructions concerning amount of curing compound, application method etc., are to be followed during execution to achieve the right efficiency. Sometimes it is necessary to change the suppliers instructions to achieve the right efficiency.

The advantages are that:

- curing compounds can be applied on fresh concrete surfaces
- when curing compound is correctly applied, no maintenance of the curing compound is required
- work traffic is relatively uncomplicated on the cured concrete surface
- it is easy to carry out evaporation protection on stripped surfaces.

On horizontal as well as on vertical surfaces it can be difficult to ensure and document that the application of the curing compound is carried out correctly.

It is not always possible to use curing compounds due to requirements concerning subsequent surface treatment. It will normally be required that curing compound is removed completely from construction joints and allways from reinforcement.

Free Surfaces
Application of curing compound on horizontal surfaces can take place concurrently with the execution of the surface finish by the contractor, so that it is not necessary to wait for large areas to be finished, or for the concrete underneath to obtain sufficient stiffness.

As the curing compound cannot be applied until the concrete surface is finished, the time when the evaporation protection should have been initiated may have been missed.

Compromises with a view to time of initiating the evaporation protection will be necessary:

- it is accepted that curing is executed later than prescribed after surface finish is completed
- another concrete composition is chosen which makes it possible to carry out surface finish and meet the requirements to evaporation protection
- the method of execution is revised.

The most common method of application is to use a sprayer. Maintenance of the sprayer as well as weather conditions make it difficult for the contractor to be certain that the work is carried out according to the instructions.

Stripped Surfaces
It is easy to apply curing compound on stripped vertical surfaces. A roll or a sprayer is used, depending on the product.

Quite often it is required that stops in the protection against evaporation, e.g. stripping and subsequent application of curing compound, must not exceed 1 hour. In case of large surfaces it may be necessary to use "professional" spray-painting equipment in order to ensure that the time-limit is observed.

3.3 Climatic Conditions

Industrial Production
Climatic control, as for instance air humidity control or establishment of curing chamber in order to meet the evaporation requirements, is mainly applied in connection with industrial production, in concrete component factories or on major jobs where serial production is required.

The advantage of this method of evaporation protection is that it is easy to carry out, control, and document, but depending on the planning of the process an extensive maintenance of the equipment will be required.

Most often the curing processes are accelerated because they are carried out at a higher temperature level which gives the best possible utilization of the equipment. It must nevertheless be taken into account that the warmer the concrete is compared to the air the higher rate of evaporation.

In Situ Production
Water curing of concrete surfaces is defined as sprinkling, irrigation or establishment of a water basin.

When water curing is used it can have an influence on the temperature elapse in the concrete. This shall of course be taken into consideration in the curing process of the structure.

Execution of evaporation protection through water curing of surfaces is not used on freshly cast surfaces as there is an increased risk that the surface finish will be ruined. This means that free concrete surfaces have to be protected during the first 24 hours otherwise.

Water curing through sprinkling is not as effective as irrigation. However, both methods can be used on horizontal and vertical surfaces.

Water curing of horizontal surfaces by means of a water basin is a powerful method which normally can only be executed on surfaces on terrain.

It may be necessary to protect against the effect from wind and sun by establishing a shelter, e.g. in case of large horizontal surfaces (bridge decks) tents are erected. However, establishment of a shelter is as such not sufficient to give full protection against drying out.

Sprinkling of vertical and horizontal surfaces is rarely used on site as it results in "anything getting wet", and as it is necessary to install alarms to prevent system failures.

The water curing method is also sorted out on account of its negative effect on the temperatures during the curing process.

3.4 Form

To use the form in order to meet the requirements concerning protection against evaporation is rather costly, especially when it is required that an extensive maturity shall be obtained. Furthermore, the various form materials provide different qualities of evaporation protection.

Therefore, the contractor plans to combine necessary form time with other protection methods, and the possibilities are described above.

There is, however, a general exception, i.e. forms for road bridges. Quite often the form on the underside of the bridge remains unstripped for a sufficient period so as to meet the requirements concerning protection against drying out. This procedure is due to the requirement on the bearing capacity/maturity before pre-stressing can be initiated.

3.5 Other Methods

The contractor may face requirements concerning the execution of the casting and a subsequent surface finish which imply that other methods of evaporation protection than the above mentioned must be considered.

The requirements in BBB [ATV-udvalget vedr. betonbygværkers holdbarhed, 1987] and AAB [Vejregeludvalget, 1994] regarding curing period are based on the assumption that the obtained relative degree of hydration of the cement shall be at least 90% in the aggressive environment. These requirements are without regard to the actual climatic condition. By using the BKI-handrule descreibed in BKI-report 3685 [Olesen, 1990] the actual curing period can be reduced, taking the actual climate and the parameters descibing the heat development of the actual concrete into account.

As an example the curing period can be reduced from the required 36 maturity hours to 20 maturity hours when a concrete which comply with the requirements in moderate environment is cast in a climate where the air temperature is 9 °C, the RH is 70% and the wind velocity is 4 m/s and the concrete surface temperature is 25 °C when the protection is removed.

3.6 Impregnation as Finishing of the Curing

Impregnation of concrete surfaces by the use of products (for example silons) penetrating into the concrete surface layer is performed at a late stage in relation to evaporation protection. Typical product requirements are that the concrete shall have reached a maturity of 28 days in order to obtain an optimum effect of the impregnation. Thus it is not documented through experience that impregnation of concrete can be performed as evaporation protection.

Through impregnation of the concrete surfaces the concrete is protected against outer influences. The effect of impregnation is due to the fact that it penetrates into the concrete surface to a certain depth, so that the concrete surface becomes tighter. The types of impregnation in use today protect against liquid such as water but allows vapour to pass. These types will therefore not provide protection against evaporation.

The effect of most of the impregnation types is increased as the evaporation degree of the concrete is increased. This does not concur with the protection against evaporation which has to be initiated immediately after concreting.

There is no experience available which sufficiently show whether impregnation of concrete surfaces can supplement or replace the traditional methods of evaporation protection.

3.7 Example of Evaporation Protection when Concreting a Road Bridge

The example below shows how the contractor carries out the evaporation protection when concreting a road bridge.

Foundations
A curing compound is applied to the vertical sides when the form is stripped (16-20 hours after concreting). On upsides a curing compound is applied, the construction joints are high pressure washed after 16-20 hours, and no further protection against evaporation is carried out.

Columns
Sides are normally stripped at a maturity in the surface of approximately 20-24 hours. A curing compound is applied, alternatively tarpaulins or Ethafoam mats are used for protection. Column top is protected with plastic foil or Ethafoam mats.

Bridge Edge Beams
"Vertical" protection after stripping is performed with curing compound, tarpaulins, Ethafoam mats or winter mats.

Upside is protected after finishing with curing compound, tarpaulins, Ethafoam mats or winter mats.

Underside is protected against evaporation with form which remains unstriped in order to meet the requirements to concrete strength before pre-stressing which is a stricter requirement than the one concerning protection against evaporation.

Bridge Slab/Bridge Wings
Generally, the upside must be trowelled, and the time for the trowelling is later than the time for initiating the protection against evaporation.

Normally, 3 procedures are used:

- the curing compound is not applied until the trowelling is carried out (the argument is that the upper concrete layer is to be removed through sand blasting with a view to execution of insulation against humidity)

or

- a membrane is applied after the trowelling is carried out (the argument is that the upper concrete layer is to be removed through sand blasting with a view to execution of insulation against humidity)

or

- a membrane is applied which must be temporarily removed in order to trowel the surface, so that the requirement concerning protection against evaporation is met. The process can be difficult to perform due to factors described in chapter 3.1

Bridge Underside/Bridge Girder
The form remains unstripped on the underside of the bridge slab and on the outer side of the bridge girder, which ensures protection against evaporation of the concrete as the form remains unstripped in order to meet requirements to concrete strength before pre-stressing which is a stricter requirement than the one concerning protection against evaporation.

After stripping a curing compound is applied to the inner sides of the girder. Alternatively protection against evaporation is performed by increasing the air humidity by means of a little water bath at the bottom of the bridge girders.

3.8 Form liner

Use of form liner is a casting method which includes curing introduced during the last years. The idea is to drain water from the concrete during the casting procedure and to let this water be absorbed by the hardening concrete. The company Du Pont manufacture a form liner called Zemdrain. The form liners influence on the quality of the concrete surface have been tested on cast concrete walls [Du Pont Nowovens, 1995].

The influence of the form liner on the quality of the concrete surface layer has been tested by use of several test methods such as hardness of the surface, surface strength, water suction, water absorption, chloride diffusien, freeze-thaw test and carbonation test. Only few information of the tested concrete are available. The water cement ratio varies between 0.45 and 0.8 and concrete with Portland cement without and with 30% fly ash, or 50 or 70% slagge has been tested. All the test results show a tremendous improve of the quality of the conrete surface layer according to the manufacturer's brochure, but no practical experience is yet available.

4. Concrete Surface Durability

4.1 Durability of the Concrete Surface Layer

The durability of concrete depends primarily on the concrete surface layer's resistance to attacks mainly from frost, water, carbondioxide (CO_2) and chlorides which can lead to deterioration and reinforcement corrosion.

To avoid frost damages the concrete surface has to be frost resistant. This is obtained by using air entrainment in the concrete and by getting a dense surface which can prevent water saturation.

To avoid attacks or at least to reduce the effect from CO_2, water and chlorides the concrete surface has to be as dense as possible and without cracks. This is obtained by using low water-cement ratio which increase the denseness of the concrete and to add fly ash to bind chloride ions in the concrete.

In practise it is difficult to determine the durability of the concrete by direct observations of the structure. The durability is therefore secured by requirements for example to water-cement ratio probably followed by tests which should be able to describe the quality of the concrete. Based on this description of the concrete quality, models can be used to predict the durability of the concrete.

The existing models to predict the durability of a concrete surface are subjected to long discussions regarding their uncertainties. However, the first step to be able to use these models is to make a precise description of the quality of the concrete surface.

Several test methods exist to determine concrete qualities and the evaluation of long term durability has made it necessary to use accelerated test methods performed in a laboratory.

4.2 Testing the Concrete Quality of the Surface Layer

To be able to evaluate the ability of the concrete to resist attacks from water, CO_2 and chlorides, test methods are used to determine the permeability, absorption, chloride penetration, number of cracks and other properties. These properties cannot directly be used to determine the durability of the concrete but they can be used to evaluate the denseness of the concrete.

However, due to the risk of reinforcement corrosion the most important issue is the denseness of the concrete surface layer which may have another denseness than the rest of the concrete if the surface layer is exposed to evaporation, poor casting/poor vibration etc. The thickness of the surface layer with another quality than the rest of the concrete depends among other things on the used curing method. If a "good" curing method has been used the surface layer may have the same quality as the rest of the concrete.

If a "poor" curing method has been used perhaps the whole concrete cover has a lower quality than the rest of the concrete.

To be able to evaluate what a "good" and a "poor" curing method is, it is important to use test methods which makes it possible to determine the quality of the concrete surface layer and not only an average quality of the whole concrete cross section.

By ranking the used curing methods after obtained concrete surface quality it may be possible to define what a "good" and a "poor" curing method is. However, the ranking may depend on the tested concrete property. If another concrete property is tested another ranking may be the result.

A number of different test methods have been developed and are used all over the world. Some of them will be described in the following.

5. Test Methods

5.1 Water Permeability

Two different test principles are often used to determine the water permeability of concrete.

One principle is to store the test specimen in a water bath and let the concrete absorb the water during a certain test period. This is a slow test method which takes several months or years to perform because the method is not accelerated. This concerns especially concrete with low water-cement ratio and without water pressure.

Another principle is to expose the concrete surface to water pressure and measure the amount of water which is pressed into the concrete during a certain test period. This accelerated test technique can be performed within a few weeks of testing, depending of the pressure.

Poulsen and de Fontenay [Poulsen, 1994] describe different test methods to determine the water permeability of concrete.

A test method following the first principle is the "converted cup method" where a concrete slice closes a cup with water which is turned upside-down. The cup is placed in a climate chamber and the weight of the cup is measured as a function of time. From these measurements transport coefficients describing the water penetration resistance of the concrete can be calculated.

Another test method described by Poulsen and de Fontenay is ISO/DIS 7031 [ISO/DIS 7031, 1983] which follows the second principle. ISO/DIS 7031 is a test method to be used in the laboratory where a water pressure is maintained on a limited area of the concrete surface. After a specified period the test specimen is split and the penetration can be measured.

Another test method which is very similar to ISO/DIS 7031 is DIN 1048 [DIN 1048, 1991].

Poulsen [Poulsen, 1985] and Neville [Neville, 1986/87] describe that the denseness of the concrete surface can be described by determining the initial surface absorption of the concrete under a pressure of 200 mm of water, which is only slightly greater than would be caused by driving rain. The test method is the British Standard BS 1881: Part 5: 1970. This test method gives information about the very thin "skin" of the concrete only.

Figg describes in [Figg, 1992] an early age permeability test method where the air and water permeability of the concrete is measured via a small plugged hole drilled from the surface of the concrete.

Nisher [Nischer, 1986] has used three different water permeability tests.

- capillary rise where the curing compound was removed by grinding and the specimens were placed on a plastic fleece immersed in water and kept there for 7 days,
- water absorption where 6 mm thick slices of concrete were dried to constant weight at 50 °C for one week and then stored under water for 4 days and
- water penetration by using Austrian Standard Önorm B 3303, with 7 bar water pressure.

Senbetta [Senbetta, 1981] has used an absorptivity test as follows. One inch diameter cores were removed from a methanol bath where they had been stored since end of curing period. The top 1 mm of the core was cut off. Then the cores were cut in 10 mm thick disks. Ethanol was used as coolant agent in the cutting process. After slicing the disks were placed in a desiccator for 48 hours, whereafter the absorptivity test was performed.

The German Standard DIN 52617 describes a capillary absorption test [Bentur, 1991]. In this method a capillary absorption coefficient is calculated from the slope of a curve showing absorbed weight of water per unit areas versus square root of time. The test procedure where specimens are owen-dried at 105 °C for 24 hrs can lead to some changes in the pore structure as well as cracking.

Another capillary absorption test method is the Danish method TI-B 25[TI-B 25, 1983] where a concrete specimen is placed in contact with water and it's ability to absorp water is measured as a function of the square root of time. Before water curing the test specimen is oven-dried at 50 °C for at least 48 hrs to obtain a suitable well-defined condition. The lower drying temperature is used to avoid changes in the pore structure as well as cracking.

After finishing the water curing the test specimen is oven dried at 105 °C and then water saturated to determine the weight of the dryed and water saturated test specimen.

This test method has been proposed to be published as a European CEN-standard.

An in-situ test method is described by Montgomery [Montgomery, 1992] where the surface absorption of concrete can be measured by an equipment called a CLAM. This is a non-destructive test equipment where a water pressure is held on the surface of the concrete for a period of time during which a fairly steady rate of flow into the surface is observed. From the measured time period and the water volume change, the flow rate which can be converted to a permeability is determined.

The CLAM technique seems to have the potential for providing meaningful results for the assessment of durability of concrete surfaces. However the results are most significant for concretes with high w/c-ratios (above 0.70).

5.2 Micro Structure of the Concrete Surface

A micro-analysis is an examination in a microscope of a thin section made from a concrete sample. This examination can be used to describe the micro structure of the concrete surface. The principle of the micro-analysis and the type of information it can give is described in details in [Jensen, 1985].

Grelk and Thaulow have in [Grelk, 1995] performed a comprehensive literature study of the correlation between defects in the micro structure and the durability of the concrete. The defects taken into account are cracks with crack widths between 0.1 mm and 0.01 mm, inhomogeneities of the cement paste and lumps of silica fume.

From the studied literature they conclude that they have only found few examples which show a correlation between micro defects in concrete and the durability.

To obtain concrete with high durability Grelk and Thaulow recommend that the - amount of defects such as coarse, fine and micro cracks and inhomogeneities of the cement paste shall be reduced as much as possible.

To evaluate the amount of such defects the test method TI-B 5 [TI-B 5, 1987] can be used.

However, Grelk and Thaulow state that in some areas this test method is not precise enough to give an unambiguous description of the amount of defects. The test method must be supplemented with measurements of the length of the cracks and evaluation of the degree of continuity of the defects.

If defects are detected through the micro-analysis more detailed information about the defects can be obtained by using a scanning electro microscope (SEMEX). To this analysis the thin section shall be covered with carbon or gold to make it electrical conducting. An example of the use of SEMEX to evaluate porosities of concrete is given in [Roy, 1983].

5.3 Chloride Penetration

Several test methods have been developed to test the concrete resistance to chloride penetration and to determine the chloride diffusivity of the concrete.

Conventional diffusion cell methods - like APM 302 [APM 302, 1991] - are used to determine the diffusion coefficient and to describe the chloride profile of the concrete. These test methods are all characterized by a testing period of at least one month and often much longer.

Rapid test methods like AASHTO T 277-83 [AASHTO T 227-83, 1983], ASTM C 1202-94 [ASTM C 1202-94, 1994] and Luping's Rapid chloride penetration method [Luping, 1992] are all characterized by a testing period of a few days. This acceleration of the testing is obtained by applying an electrical field on the test specimen.

The result of the AASHTO and the ASTM method is the amount of Coulombs which have passed through the test specimen. This result gives no information about the diffusion of the chloride ion itself in concrete, but the electrical resistance corresponds to the diffusivity of the concrete.

Luping's method gives more information than the amount of Coulombs. After the test the specimen is splitted and the chloride penetration depth is determined by using the colorimetric method [Collepardi, 1970] and the chloride profile is determined from slices of the test specimen.

5.4 Carbonation

The test method NT BUILD 357 [NT BUILD 357, 1989] can be used to determine the carbonation depth of a concrete specimen which has been exposed to a high concentration of CO_2 for a certain period.

The testing is normally continued for a period of at least three months but preliminary results can be determined already after one or two weeks.

The carbonation test method recommended by RILEM Committee CPC-18 (measurements 1984) [Bentur, 1991] can also be used to determine the carbonation depth. The depth of carbonation is determined on splitted surfaces of concrete. The concentration of CO_2 can be varied.

5.5 Strength

In many test programs about the effect of curing on durability the compressive strength of the concrete is tested. This is for example described by Montgomery [Montgomery, 1992] who has determined compressive strengths on cubes and surface strengths by the use of in-situ pull-off testing.

The results of these tests show that the measured surface strength is significantly lower than the measured cube strength. Further, it is concluded that different curing regimes have greater effect on the surface strength than on the overall strength determined by cube testing. However, the effect is most significant for concrete with high w/c-ratio (0.70 or higher).

Montgomery has also tested the surface strength by measuring the abrasion resistance of the concrete surface. The results show increased abrasion depth with lower surface strength but no unambigueus correlation between the two parameters can be defined.

Also Nischer [Nischer, 1986] has used compressive strength testing on drilled core specimens of 5 cm diameter. Nischer concludes that the strength reduction can be detected to a depth of about 10 cm. The strength test provides only limited information in cases where curing is deficient.

Alsayed [Alsayed, 1994] has used compressive strength testing too. Alsayed concludes the compressive strength test to be good to distinguish between cured and uncured concrete.

5.6 Sealant Penetration

Stewart and Shaffer [Stewart, 1969] describe a method developed to measure the depth of penetration of curing products as follows:

Since many of the products were neutral in colour a colouring agent called "Black-Ray" was used which was of a low viscosity of organic origin. It was fluorescent under ultraviolet light, and was soluble in all products tested. The concrete subjects treated with the curing products were broken in two, and half a section was placed under the binocular microscope of the linear traverse apparatus with the broken face upward. The sample was positioned so that the microscope could be focused on the treated edge within the central portion. An ultraviolet light was directed on the sample and as the microscope picked up a trace of fluorescence the sample was traversed to the end of penetration. The method was evaluated as well-functioning.

6. Previously Performed Curing Tests

This paragraph contains results of curing tests performed both in laboratory and in the field. All tests are performed on small test specimens often cubes or cylinders cast in the laboratory. The laboratory climate and the used test methods are varied in the different tests.

6.1 Laboratory Tests

Bentur and Jaegermann [Bentur, 1991] among other subjects have studied the effect of curing on the quality of concrete skin. The experimental study consists of various water-curing treatments in different environmental conditions. The water treatments were 5 minutes immersion in water, twice daily, of concrete cubes and prisms over 0, 1, 2, 3 and 6 days and a reference where cubes were kept in water for 6 days. The specimens were exposed to two different environmental conditions - 20°C and 65% RH; and 30°C and 40% RH - in a wind tunnel. The specimens were tested after 28 days.

The compositional variables of the concretes in this study included W/C-ratio in the range of 0.45 to 0.80, with the concrete consistency being kept constant at about 100 mm slump. This was achieved by varying the cement content in the range of 230 - 430 kg/m^3. The effect of fly ash was studied in concretes having the same standard cube 28 days compressive strength of about 33 MPa. This was achieved by cement replacement in the mass ratio of about 1:2, with the fly ash content being 25% and 40% by weight of cement. The fly ash replaced part of the cement and part of the sand. The concretes were mixed in batches of 0.05 m^3 and the maximum aggregate size was 20 mm.

An accelerated and a normal carbonation test and rate-of-absorption test have been used evaluating the quality of the concrete skin. The methods can provide information of at least semi-quantitative significance. The absorption test was carried out in accordance with the German Standard DIN 52617. Also carbonation tests have been used in this study using the procedure recommended by RILEM Committee CPC-18 (measurements 1984). The concentration of CO_2 has been 5% which is on the high side. Also normal concentration of CO_2 has been used for up to three years. Bentur concludes that the depths of carbonation at any given time and rates of carbonation are sensitive to curing. Use of absorption test should be used with care because the test results are sensitive to the moisture content of the concrete. If the absorption test is properly interpreted it can provide a semi-quantitative assessment for the quality of the concrete skin.

Balayssac, Détriché and Grandet [Balayssac, 1995] have made a study on the durability of concrete cured under different conditions expressed in terms of carbonation depths.

A limestone filler cement containing 25% of limestone fillers, an ordinary Portland cement and a slag cement with 65% of slag were mixed. The sand and gravel are river aggregate with a maximum size at 12.5 mm. The strength varies from 25 to 40 MPa.

The consistency were kept constant at 8 cm and the water-cement ratio varies between 0.48 to 0.73. The cement content varies in the range of 250 to 420 kg/m^3.

The test results have shown that curing conditions and especially curing time have a significant effect on the durability of commonly used concretes. The test samples were demoulded after one day and stored in controlled environment at 20°C and 60% RH or kept in water up to 3 or 28 days before exposure to the environment described above. The test samples were stored up to 18 months.

The carbonation depth was measured with reference to RILEM recommendation, TC56-MHM Hydrocarbon materials, CPC-18 Measurements of hardened concrete carbonated depth, on split test samples.

Senbetta [Senbetta, 1981] has made some tests on mortar with different curing regimes. Five different curing conditions have been evaluated. The mix proportions for the mortar consists of a water-cement ratio of 0.5 and a sand to cement ratio of 2.74. The conditions were curing compound, plastic cover, unprotected and exposed with wind, unprotected and wet burlap. All samples were cured at 22% RH for a duration of 1, 3 or 5 days. Senbetta concludes that absorptivity tests used on concrete may be used as indicators of good or bad curing conditions.

The study includes the British test method BS 1881: Part 5: 1970 and Figgs method, both described in paragraph 5.1.

Suprenant and Tumasulo [Suprenant, 1994] also recommend water absorption test as a method to differentiate the effectiveness of different curing methods on the quality of the concrete. The RILEM water absorption test has been used. As expected the test results are affected by the moisture content of the concrete. It is necessary to ensure that the moisture content of the concrete specimens is at the samme level. The concrete used were an air-entrained normal weight concrete with a compressive strength at 21 MPa, slump at 12 - 18 cm, air content at 4 - 7% and a water-cement ratio at 0.49.

In [Suprenant, 1994] a combination of curing methods, both water-adding (placing in moist curing room and covered with wet burlap) , water retaining (curing compounds) and air-drying (on enquiry) were used.The form stripping time were 1, 3 or 7 days. The study took place in a laboratory with 70°F and 34% RH. All curing methods were stopped after 28 days. Application of wet burlap or curing compound was appropriate in this test.

Nischer [Nischer, 1986] has tested the effect of curing on various properties of the concrete. The capillary rise test method, the water absorption test method and the water penetration by using Austrian Standard Önorm B 3303 made it possible to register differences in curing conditions.

The investigations were carried out on concrete specimens (60 x 60 x 30 cm), demoulded after 5 hours, partly provided with curing compound (RVS 11 064) and partly untreated. The water-cement ratio varies between 0.4 and 0.7.

Thomas and Matthews [Thomas, 1994] conclude that oxygen permeability tests indicate a very pronounced dependence on the duration of curing. The tests were performed on discs 150 mm in diameter and 50 mm thick cut from 150 x 300 mm cylinders. The specimens were conditioned at 20 °C and 65% RH for 28 days before testing.

Three series of concrete mixes were designed using a range of fly ash levels, 0%, 15% and 30%. The characteristic design strengths were 25 MPa, 35 MPa and 45 MPa. The slump ranged from 30 to 60 mm.

The authors also conclude that test results from carbonation tests and oxygen permeability tests appear to be in conflict.

The test program included the following curing conditions:

After casting the specimens were cured for 24 hrs in moulds under damp sacking and polyethylene either in the laboratory at 20 °C or in a climate cabinet at 5 °C. After 24 hrs, all specimens were demoulded, stored at the same temperature and subjected to one of the following curing treatments:

- 1-day cure: air stored immediately after demoulding
- 3-day cure: moist-cured under damp sacking and polyethylene for an additional 2 days before air-storage
- 7-day cure: moist-cured as described above for an additional 6 days before air-storage
- water-cured: immersed in water for 28 days.

After curing the specimens were stored in air at 5 °C or 20 °C and relative humidities were 40, 65, 80 or 90%, respectively.

Stewart and Shaffer [Stewart, 1969] describe a test method used to measure depth of sealant penetration into the surface of a typical concrete structure.

Two types of mixes were used. One called C is based on a mix proportion (cement:sand:gravel) 1:2.75:2.75 and one called A is based on 1:1.74:3.40. The slump varies from 1 to 7 cm. 12 series are made with the mix C and only one with the mix A.

The method was good, but apparently there was no correlation between the depth of penetration of the sealer and the final rating of the product. The method is described in section 5.6.

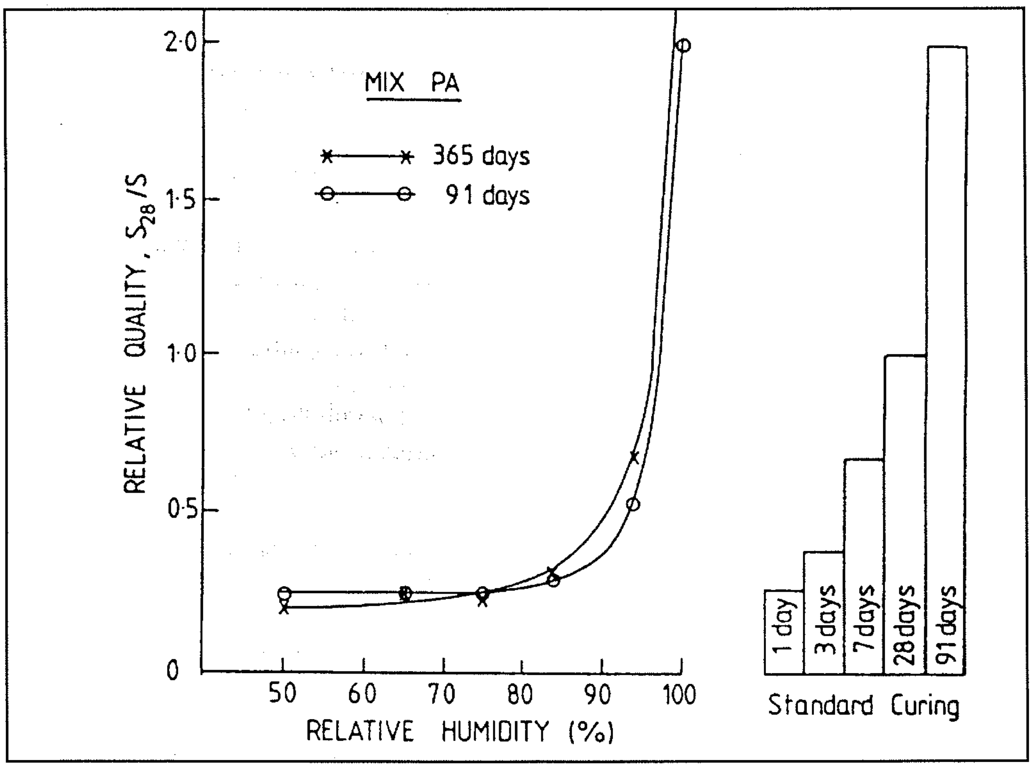
Montgomery, Basheer and Long [Montgomery, 1992] have tested the effect of three different curing regimes on five different concrete types with w/c-ratios from 0.40 to 1.00.

The obtained quality of the concrete has been described by the cube strength, the surface strength, the surface permeability and the surface abrasion. All tests of the surface quality have been performed in-situ. The results show that differences in curing are reflected as differences in the concrete properties. These differences are magnified at the surface, particulary for materials having a high w/c-ratio, and are always such as to degrade the durability of the surface.

Ho, Cui and Ritchie [Ho, 1989] present a figure of the achieved quality of concrete exposed to different relative humidities. Five mixes with a 28 day compressive strength around 32 MPa were used. The cement content varies from 260 to 354 kg/m^3 with a water-cement ratio between 0.58 and 0.64. Two of the five mixes contain 20% fly ash.

The figure shows a rank of the different curing methods as a function of the obtained concrete quality like the one we have in mind in this research project. In [Ho, 1989] the quality of the concrete is studied in terms of water sorptivity by means of water penetration due to capillary action.

Figure 6.1: Quality achieved by concrete exposed to different relative humidities [Ho, 1989].



Lundberg [Lundberg, 1994] presents the results of a comparative testing of different curing procedures performed by DTI and Dansk Beton Teknik A/S. The purpose of the testing was to compare different curing methods for anchor block splay chambers and splay saddel legs to the Danish Great Belt East Bridge.
The tested curing methods are shown in figure 6.2.

Figure 6.2: Tested curing methods.
(PFL) means that the concrete was cast against a permeable form liner.

Test specimen	**Form period**	**Remarks**
A1	0 - 240	Reference
A2	0 - 240	Reference
A4	0 - 240	Reference. One layer of sealing compound one hour after stripping.
B1	0 - 72 (PFL)	Two layers of curing compound.
B3	0 - 96	One layer of curing compound.
B2	0 - 72	One layer of curing compund.
C2	0 - 72	
C4	0 - 72	One layer of sealing compound one hour after stripping. Curing compound applied at 77 M-hours.
B4	0 - 72 and 72 - 240	110 - 120 g/m^2 water applied at 72 M-hours. One layer of sealing compound one hour after the final stripping

The objective was comparative testing of the following:

- total weight loss from the concrete specimens;
- petrographic testing of three thin sections taken in the surface of each specimen;
- water absorption testing according to NT BUILD 342;
- evaluation of the depth of penetration of the curing and sealing compound;
- LOK testing to determine surface strength.

The concrete tested were a three powder concrete with a water cement ratio below 0.4.

The results of the testing was summarized as follows:

- the weight losses were relatively small for alle test specimens, and for the PFL treated test specimen it was particularly low;
- the number of micro cracks and the depth of penetration of curing and sealing compound are shown in figure 6.3 together with the results of the absorption testing;
- the LOK testing showed the same surface strength of all specimens.

Figure 6.3: Obtained test results.

Test specimen	**Micro cracks from surface (per 45 mm)**	**Depth of penetration of curing or impregnation compound**	**Absorption (g/m^2)**
A1 (ref.)	7	-	233
A2 (ref.)	5	-	330
A 4 (ref.)	6	0*	-
B1 (PFL)	2.3	0 - 0.1 mm	77
B3 (96 Mh)	1	0.5 mm	66
B2 (72 Mh)	0	0.5 - 1 mm	62
C2 (72 Mh)	0	0.5 - 1 mm	83
C4 (72 Mh)	0	1 - 2 mm	-
B4 (water)	5.7	0*	-

* It was not possible to detect the sealing compound.

From the performed tests it was concluded that the reference method with the long form period apparently gives the worst quality of the concrete surface compared to all the alternatives using curing compound as protection during a part of the curing period.

Further, it was concluded that sealing after application of curing compound was not a feasible method but to do it in the reverse order might however be a good solution.

In the referred laboratory tests different types of absorption tests, carbonation tests and other types of permeability tests have been used.

In most of the references the carbonation test is recommended as indicator of good or bad quality of concrete skin. The different permeability test are recommended to be used with care.

6.2 Field Tests

All field tests reported in the following have been performed on laboratory test specimens exposed to different curing regimes and afterwards placed in the field. No literature references on field tests on full scale constructions have been found.

The Swedish National Testing and Research Institute has performed an extensive study on the influence of curing conditions on permeability and durability of concrete. The study included both laboratory tests and field exposure tests and the results of the tests are presented by C. Ewertson and P.E. Petersson in [Andersson, 1987], [Ewertson, 1992] and [Ewertson, 1993].

The results indicate that water curing is superior to the other curing methods such as covering by plastic foils or membrane curing compounds. It is also reported that bad curing conditions during the first days after casting to a large extent can be compensated by use of a renewed wet curing [Andersson, 1987].

In [Ewertson, 1992] and [Ewertson, 1993] it is reported that the drier climate, the more pronounced the difference between different curing conditions will be. And they conclude that laboratory tests cannot always be used to predict concrete behaviour in a real structure. Field exposure tests are to be preferred [Ewertson, 1992].

Based on the performed tests it is concluded, that the tests seem to indicate that water curing and plastic foil are equally efficient for producing good quality and that no curing gives much poorer results [Ewertson, 1992].

The influence of the curing method on the quality of the concrete surface layer have been registered by use of parameters such as water tightness, air permeability, carbonation rate, chloride penetration rate, salt frost resistance and surface tensile strength.

The results from the chloride penetration tests and the salt frost resistance tests are not very sensitive to different curing methods. Because of the long test period where the concrete surface is in contact with water [Ewertson, 1992].

Measurement of water tightness (or water impermeability) by use of pressure is a quick and easy method which shows big differences between good and bad curing conditions, but the results are at least to some extent contradictory to the results from carbonation tests [Ewertson, 1992].

The test method surface tensile strength is not sufficient because it gives contradictory results depending on how many mm of the surface layer is tested [Ewertson, 1992].

The different curing conditions used in the field tests are shown in figure 6.4 below [Ewertson, 1993].

Figure 6.4: The different curing conditions used in the field tests [Ewertson, 1993].

Type of curing	Time until form removal [1)] (days)	Water curing (days)	Covered with plastic foil (days)	In the air (RH=50%) (days)	Curing time at 20°C, t_{20} (hours)
W0	0	5	0	23	120
PF0	0	0	5	23	120
A0	0	0	0	28	0
W1	1	5	0	22	144
PF1	1	0	5	22	144
A1	1	0	0	27	24
W3	3	5	0	20	192
PF3	3	0	5	20	192
A3	3	0	0	25	72

[1)] 0 days before form removal is relevant only for the horizontal top surfaces of the specimens while 1 and 3 days before form removal are relevant for surfaces cast against the mould.
(W = water, PF = plastic foil, A = air and 0, 1 and 3 represent the number of days before form removal).

Marsh and Ali have assessed the efficiency of curing on the durability of reinforced concrete published in [Marsh, 1993]. Use of curing compound has not been included in the field tests. The specimens have been cast in the laboratory and after demoulding and completion of curing the specimens have been subjected to outdoor exposure.

The report concludes that curing methods where free water is applied to the concrete surface are more effective than methods aimed to prevent or limit moisture loss. It also concludes that normal variability within a concrete may be greater than the measurable effect of commonly used curing methods.

In [Ljungkrantz, 1988] and [Lind, 1992] Cementa has reported some research of long-time field tests on concrete constructions. The curing conditions have been as follows:

- after stripping the concrete surface covered with wet burlap has been covered with tight plastic foil for 6 days at 20°C. Afterwards the concrete specimens has been kept in the laboratory at 20°C for 7 days

- after stripping the concrete specimens have been stored uncovered in the laboratory at 20°C and 40-60% RH for 7 days. Afterwards the specimens have been covered with wet burlap and tight plastic foil for 6 days at 20°C.

11 different concrete types have been tested. 4 different cement types - two Portland cements and two Portland fly ash-cements - were tested, one of them with 10% silica. The water-cement ratio was for 8 of the concretes 0.6. The three others were 0.43, 0.45 and 0.8.

Among other things the rate of carbonation for the two different curing regimes has been tested. The reports conclude that a good curing with rain fall on the concrete surface is able to increase the protection against carbonation.

This means that differences in the curing periods at the early stage can be overruled by placing the concrete surfaces in an environment with a high RH.

Also Alsayed and Amjad [Alsayed, 1994] conclude that water absorption is a test method usable for evaluation of the effect of curing method. The concrete mix composition used 486 kg cement per m^3, 1020 kg aggregate and 680 kg sand with a water-cement ratio at 0.45. The maximum aggregate size is 20 mm and the compressive strength 35 MPa.

The test program includes casting of concrete slabs and cylinders in steel moulds covered with burlap for the first 24 hrs. After stripping the specimens were exposed uncovered for 300 days to field conditions after curing conditions as follows:

- sprinkled with water twice a day for the first seven days after casting
- covered with burlap and sprinkled with water twice a day
- covered with impervious polyethylene sheet
- exposed to air untreated.

The field conditions were characterized by maximum daily temperature in excess of 45°C, diurnal variations in excess of 20°C, relative humidity less than 15%, average wind velocity of 6 m/s and solar radiation of 600 w/m^2. In [Alsayed, 1994] it is also concluded that curing with sprinkling water twice a day decreases the water absorption by 20 % compared to uncured concrete.

7. Existing Models for Curing versus Surface Quality

In the studied literature the following models for curing versus surface quality have been found.

7.1 Evaporation

In the Explanatory document to BBB [ATV-udvalget vedr. betonbygværkers holdbarhed, 1986] evaporation rate of water from the wet surface is described from the expression as follows:

$$\dot{w} = (0.015 + 0.011 \cdot V)\, \Delta P$$

where

$\dot{w}$	evaporation rate kg/m^2h
V	wind velocity m/s
ΔP	vapour pressure mm Hg

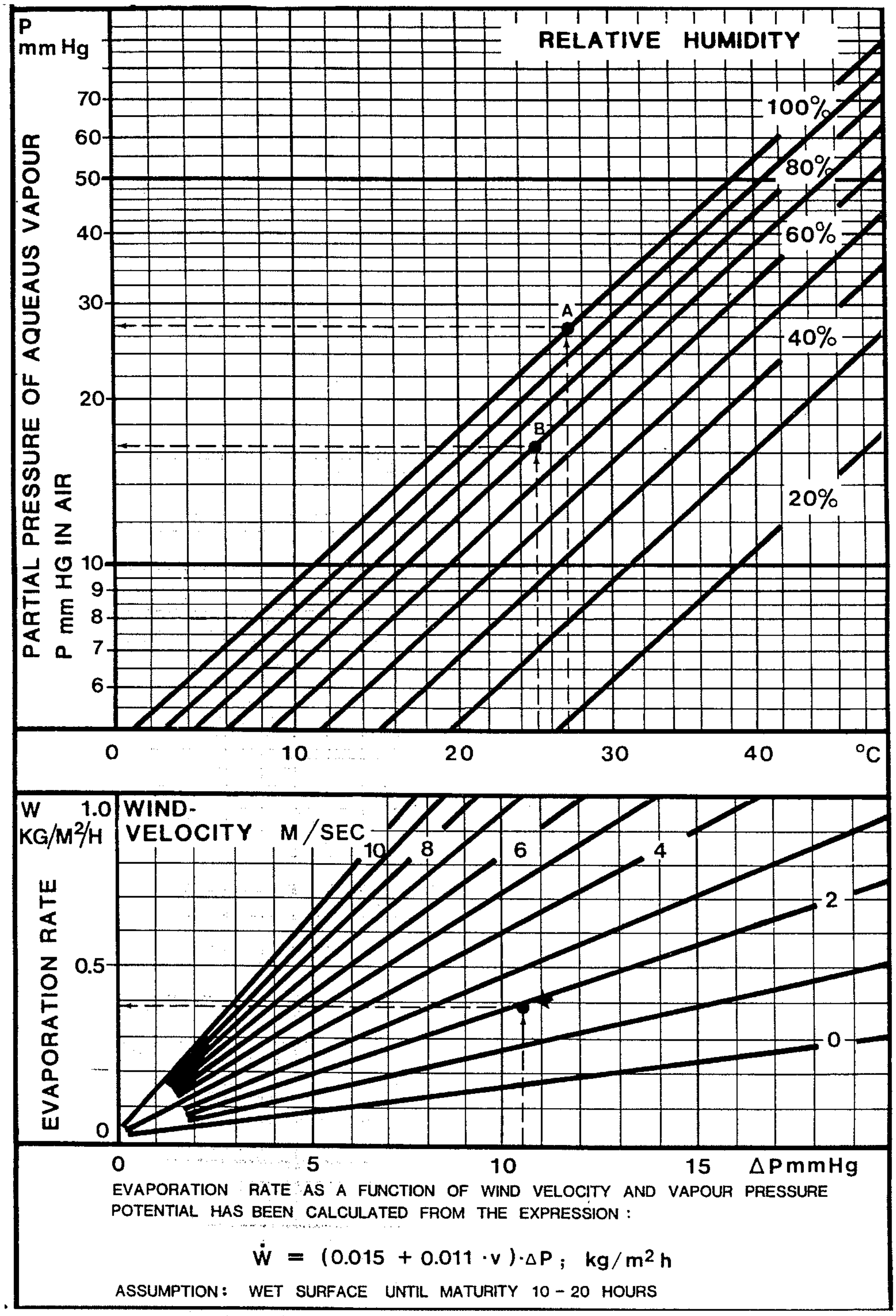
The assumption is valid for a fresh concrete surface until maturity 10-20 hours corresponding to the setting time of the concrete.

As long as the concrete is fresh, water can evaporate from the concrete surface like from a wet surface. Differences in the partial steam pressure in the concrete and in the air control the evaporation rate together with the wind velocity. The relative humidity in the fresh concrete is 100% and in the air it is normally less than 100% and typically 70%. The partial steam pressure depends primarilly on the temperature differences in the way that concrete warmer than the air will cause rapid evaporation.

A negative patial steem pressure difference (concrete somewhat colder than the air) will result in condensation on the concrete surface. On the other hand it must be strongly emphasized that concrete warmer than the air can have a substantial evaporation rate <u>even if</u> the RH in the air is 100%.

The evaporation can be evaluated from figure 7.1.

Figure 7.1 Evaporation rate. [ATV-udvalget vedr. betonbygværkers holdbarhed, 1986]



7.2 Carbonation

Nagataki, Ohga and Kim [Nagataki, 1986] describe a model of the relation between the rate of carbonation and the type of cement, environmental conditions, water-cement ratio and the microstructure of concrete. The equation below has been obtained by using the results of the tests performed and reported in [Nagataki, 1986].

$$X = AB\,(\alpha\,(W/C) - \beta)\,t^{\delta}$$

where
- x: depth of carbonation (cm)
- A: correcting factor
- B: factor for initial curing period in water
- α, β: factors for fly ash
- W/C: Water-cement ratio
- t: age (year)
- δ: factor for environmental conditions

Based on the test results the coefficients of equation are as shown in figure 7.2

Figure 7.2: Coefficients of equation [Nagataki, 1986]

Exposure Condition	F/(C+F) (%)	A	B	α	β	γ
Outdoors	0	0.55	1	4.211	1.831	0.25
	30	0.77		3.311	1.777	
Indoors	0	1.50	1.00 (for 7 days *)	1.656	1.656	0.5
	30	1.61	0.78 (for 91 days *)	1.445	0.619	

Figures 7.3 and 7.4 show the comparison of the Estimated Values with the test result.

In [Nagataki, 1986] the authors conclude among other things that the initial curing period affects the carbonation of concrete cured indoors and the carbonation of concrete cured outdoors is not affected by the initiated curing in water.

Figure 7.3 Comparison of Estimated Values with Test Results (outdoors) [Nagataki, 1986].

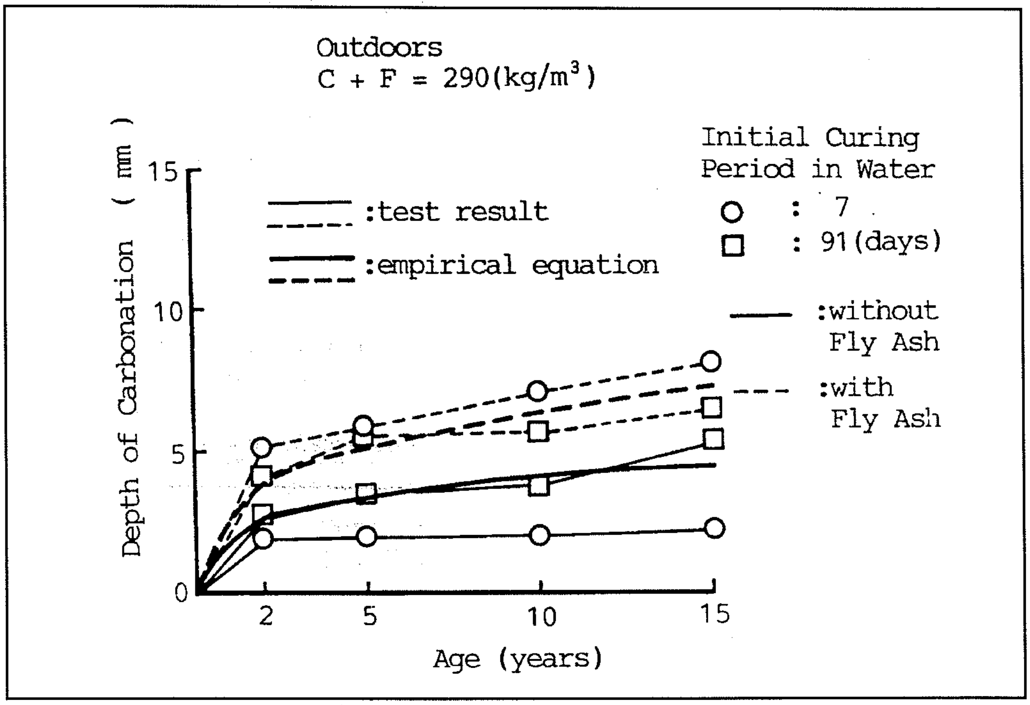
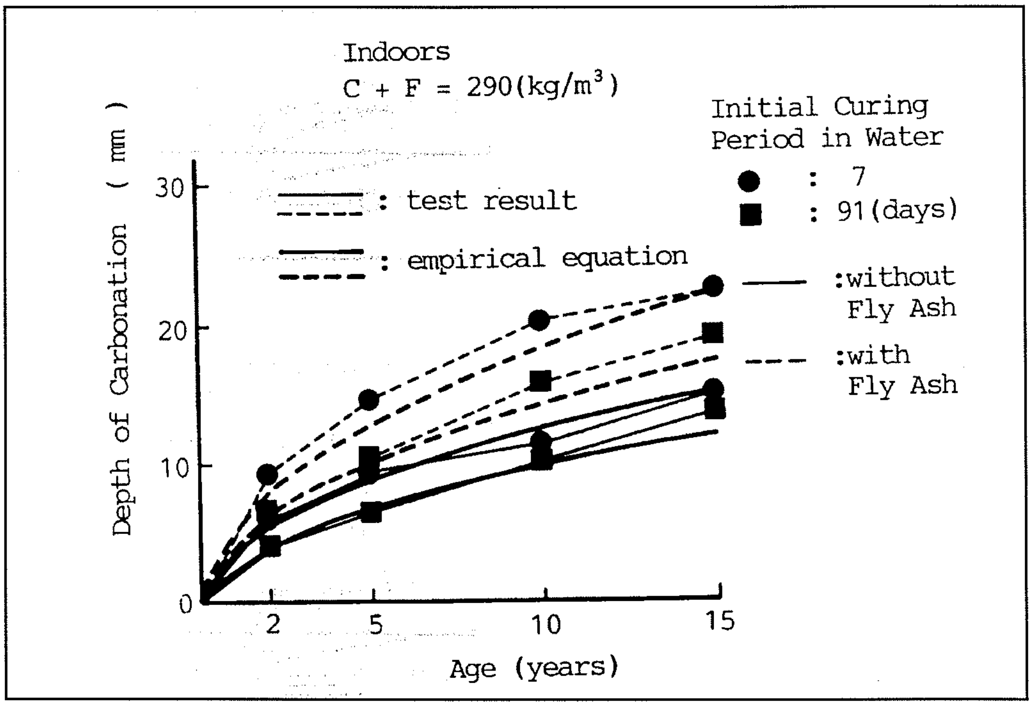


Figure 7.4: Comparison of Estimated Values with Test Results (indoors) [Nagataki, 1986].



Bentur and Jaegermann [Bentur, 1991] describe the depth of carbonation as follows:

$d = Kt^{1/2.5}$

where d = depth of carbonation at time t

t = duration of carbonation (accelerated and natural)

K = constant typical of the composition and curing of concrete.

In [Bentur, 1991] the relation between the natural (k_n) and accelerated (k_a) carbonation is described as follows:

$K_a = 7.5\ K_n$

8. Conclusion

From this State of the Art regarding curing the following can be concluded:

In the existing Danish concrete specifications the requirements to curing are based on the State of the Art of 1986. No further development of the main theory has been performed during the last 10 years.

A number of tests have been performed worldwide to evaluate different curing methods and their influence on the concrete surface quality. A lot of different test methods have been used to describe the obtained quality by means of absorption tests, carbonation tests and other types of permeability tests.

The tests have shown that:

- the best concrete surface quality is obtained by using water curing and
- if no protection of the concrete is performed the quality will be reduced.

When using curing methods between these two extremes the obtained surface quality obviously depends primarely on the test method used to measure the quality.

However, some results have indicated that a poor surface quality can be improved by water curing performed at a later stage. Further, when the concrete is exposed to the weather conditions in the field an improvement of the surface quality can be obtained.

Most of the performed tests have been based on the principle: test and observe without modelling of a theory in advance. This is probably caused by the fact that only a limited number of models exist to describe the correlation between the curing method and the obtained surface quality. Moreover, many tests are not performed with enough control of temperature, RH, wind velocity etc. to enable modelling of the results.

To be able to improve the contractors curing technology and establish a better basis for development of valid models for curing versus surface quality research will be needed such as:

- Performance of controlled tests of curing methods in the laboratory
- Performance of controlled tests of curing methods in the field
- Evaluation of the obtained surface quality by use of a number of test methods
- Evaluation of the most appropriate test methods for surface quality description
- Ranking of different curing methods with regard to surface quality
- Modelling of the above.

In the future further research will be needed in order to:

- Describe the correlation between obtained surface quality and the durability of the concrete structure
- Verify the models under a wide range of other conditions and with a wide range of different concrete types.

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