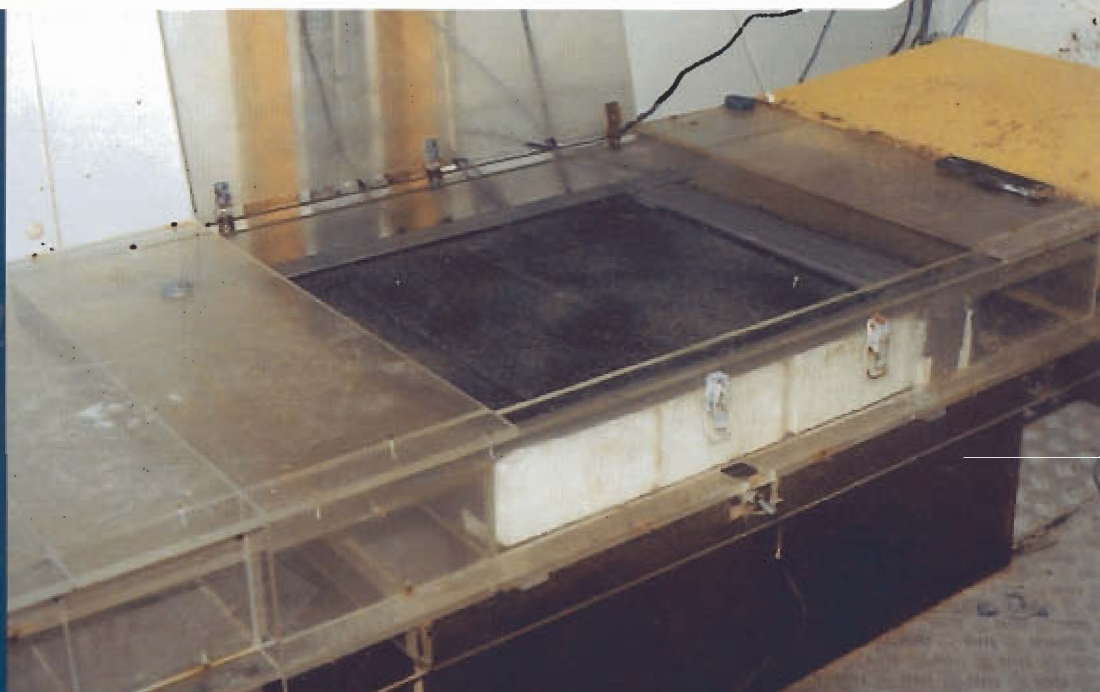
HETEK

Curring
Phase 1: Laboratory Tests



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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.

In Phase 1: Laboratory Tests, fourteen different curing methods are tested in DTI's laboratory, where it was possible to expose the concrete surface to a controlled temperature, relative humidity and wind velocity. At the same time the evaporated amount of water from the concrete surface was weighed continously. The fourteen curing methods are based on the contractors experience and includes also the extreme methods such as water curing and no protection. All the tests were performed on a typical concrete used for bridge constructions.

The quality of the concrete surface were expressed based on testing of the parameters micro structure including a description of the cracks, resistance to chloride penetration, capillary water absorption and resistance to carbonation.

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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 contractor's design of high performance concrete and execution of the concrete work with reference to obtain the requested service life of 100 years.

The research programme is divided into 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.

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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.

December 1996
Per Fogh Jensen
Marlene Haugaard
Steering Committee of
HETEK-Curing project

1. Introduction

With reference to the supplementary research report HETEK - Curing - Supplementary research - Proposal [Haugaard and Berrig, 1996, Phase 1], testing of fourteen different curing methods in laboratory are described in this report. These tests perform part of the background for preparing a guideline concerning curing of concrete as described below.

Curing of concrete is required to ensure a good quality of the concrete surface layer meaning a dense concrete without cracks. The good quality shall ensure a long durability of the concrete structure. This involves protection both of the fresh concrete and during the first time of the hardening period. The protection shall ensure the concrete against destructive evaporation.

In practise these damages 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 todays concrete specifications for construction projects requirements regarding curing are stated. The requirements normally state how early and how long the concrete surface shall be protected against evaporation. In the last years there has been a tendency to more and more strict requirements meaning earlier protection and longer protection period.

Some investigations performed by DTI and Dansk Beton Teknik A/S [Lundberg, 1994] have indicated that a shorter period with formwork on the concrete surface combined with a curing membrane result in a higher quality of the concrete surface expressed as number of micro cracks compared with concrete protected with formwork for a long period.

It is therefore desirable to get more information about how effective the curing must be to obtain a concrete surface of high quality.

The aim of the laboratory testing is to rank different curing methods as a function of obtained concrete surface quality. These information shall be used if possible in a revision of the existing requirements concerning time of protection, protection period and type of protection.

2. Test Programme

Phase 1 of HETEK - Curing consist of a laboratory test of fourteen different curing methods. Each curing method is tested on a concrete specimen which an evaporation test. The evaporation test performed in is a windtunnel which is placed in a climate cabinet to control the climate conditions. The evaporation in a period of 10 days - from the time of mixing of the concrete - is measured and after 28 days the quality of the concrete surface is expressed by different test methods. The obtained test results are to be evaluated in phase 2.

The fourteen different curing methods are described in chapter 2.1. When testing the fourteen different curing methods the time, the climate and the weight loss are automatically recorded. The concrete used for the specimens cast for the different curing methods is described in chapter 2.2. The evaporation tested is described in chapter 2.3. The specimens weight losses are described in chapter 2.4. In chapter 2.5 are the quality of the concrete surface described by four different test methods.

2.1. Curing Methods

Fourteen different curing methods were chosen on the contractors experience which again are based on how practical and economical the curing methods are. They include often used curing methods and also some extreme curing methods such as water curing and no protection. The extreme curing methods were chosen because they presumably will be a help concerning the description of theory which is the phase 2 of the supplementary research.

Figure 1. Test programme of 14 different curing methods.

Test no.	Mould	Free surface	Surface: Curing compound	Surface: 10 mm DOW-matt	Surface: Wet surface
	Mh	Mh	Mh	Mh	Mh
1	0-72	72-240	-	-	-
2	0-72	72-74	74-240	-	-
3	0-240	-	-	-	-
4	-	0-240	-	-	-
5	0-24	24-240	-	-	-
6	0-24	24-26	26-240	-	-
7 *	-	0-240	-	-	-
8 *	0-72	72-74	74-240	-	-
9	-	0-4/8	4/8-240	-	-
10	-	0-4/8	-	-	4/8-240
11	0-24	24-26	-	26-240	-
12	0-72	72-74	-	74-240	-
13	-	0-4/8	-	4/8-240	-
14	-	0-2	2-240	-	-

In figure 1 the fourteen different curing methods are given. The time is given in maturity hours (Mh) after mixing. The evaporation tests varying in curing period being in close and open mould, relative humidity and the curing period being cured with curing compound, water or protected with a DOW-matt.

All evaporation tests were performed in a period of 10 maturity days with the climate conditions app. 20 °C. For all the tests except test no. 7 and 8 the relative humidity were app. 70 %. For test no. 7 and 8 the relative humidity were app. 50 %. For the period with free surface the wind velocity was app. 3.6 m/s.

For some of the curing methods the time is given as 4/8 maturity hours. This is because the setting time of the concrete was unknown at the time where the tests were planned.

The setting time of the concrete is defined as the period from time of mixing and until the strength development of the concrete begin.

In HETEK control of Early Age Cracking, Phase 1 is the setting time determined from the heat development curve at the deflection tangent intersection with the maturity axis. The setting time is determined to app. 5 maturity hours.

For those curing methods which include curing compound app. 234 g/m^2 curing compound was sprayed on the surface in an even layer. The chosen curing compound is based on water and ester with an efficiency of 84 % according to TI-B 33.

The density is 930 kg/m^3 with a solid content of 55 %. The required quantity is 250 ml/m^2 which is app. 233 g/m^2. The weight loss from the curing compound was tested separately for the first 240 maturity hours thus the weight loss from the specimens cured with curing compound could be corrected for the weight loss of the curing compound. The test was preformed at the same time as test no. 3 thus the weight loss from test no. 3 only is recorded after 240 maturity hours. This is chosen as the weight loss from test no. 3 is nearly zero.

For test no. 11-13 a 10 mm DOW-matt was laid on the surface. To ensure that the DOW-matt was kept down to the surface some weight was placed around the border.

The wet surface in test no. 10 was provided by using a wet sack being watered daily.

The time is given in maturity to make allowance for the hardening dependence on the temperature. This is due to the chemical reaction between the cement and water pass of rapidly the higher the temperature is. The time expressed in maturity correspond to the chemical reaction which takes place at 20 °C. The following formula is used to calculate the time in maturity.

$$H(\theta) = \frac{The\ rate\ at\ \theta\,°C}{The\ rate\ at\ 20\,°C} = \exp[\frac{E}{R}(\frac{1}{293} - \frac{1}{273+\theta})]$$

where	E = Activation energy	= 33500 J/mol,	$\theta \geq 20$ °C
		= 33500 + 1470(20-θ) J/mol,	$\theta < 20$ °C
	R = The gas constant	= 8.314 J/mol	

2.2. Specimen

To each curing method one specimen was cast. The specimen was cast in a mould of plexiglass with a surface of 450 x 550 mm and a thickness of 100 mm. The concrete used has a maximum equivalentwater-cement ratio on 0.40, low-alkali sulfatresistant cement, fly ash, silica fume, seasand, granite and entrained air. The concrete mix design for all the specimens is shown in figure 2.

Figure 2. Concrete mix design.

Recipe No. 6021 from 4K-Beton

	Type/origin/class	kg/m^3
Cement	Low-alkali Sulfatresistant CEM I 42,5(HS/EA/≤2)	285
Fly ash	Danaske	60
Silica fume	Elkem	12
Water	Water	127
Fine aggregate	RN, Avedøre sand 0/4, SA	758
Coarse aggregate	Rønne granite 8/16, A	535
Coarse aggregate	Rønne granite 16/25, A	565
Air entrainment	Conplast 316 AEA, Fosroc	0.357
Plasticiser	Conplast 212, Fosroc	1.428
Superplasticiser	Peramin F, Fosroc	2.856
Equivalent water-cement ratio		0.38
Content of FA+MS by weight of C+FA+MS		20.2 %
Content of MS by weight of C+FA+MS		3.4 %

The surface for eight of the fourteen specimen was cast against an 18 mm waterproof plywood plate which was placed on the plexiglass-mould. Form oil was used on the plywood plate. The form oil was based on water and ester.

Immediately after casting the specimen was placed in the evaporation test and cured as described in chapter 2.1. Each specimen was marked after the curing method.

2.3. Evaporation Test

The test equipment is the same as described in TI-B 33: Determination of the Efficiency of Concrete Curing Compound [TI-B 33, 1992].

After casting the specimen was removed to a windtunnel in a climate cabinet where the temperature and the relative humidity can be kept approximately constant. The temperature was measured by using a thermocouple (copper/constantan) which was placed in the middle of the climate cabinet. The humidity was automatically controlled and measured. In the windtunnel the surface of the specimen was exposed to a well defined laminar air flow. Figure 3 show a photo of the windtunnel. The wind was established by using a ventilator which absorb air through the tunnel and measured by using a Therm rotor anemometer. The anemometer was placed in the middle of the wind tunnel 30 mm above the free surface of specimen. Inside the windtunnel a scale was placed thus the weight was recorded continously. Further the temperature in the specimen was measured by using a thermocouple cast in the center of the specimen.

Every 10 minutes from time of casting the temperatures, relative humidity, wind velocity and weight was measured automatically through the test period which was the first 10 maturity days from mixing.

Figure 3. Photo of the windtunnel.

2.4. Weight Loss

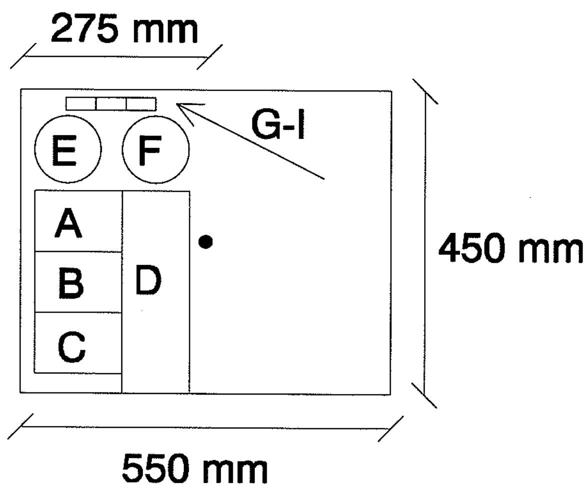
In order to obtain a good quality of the concrete surface layer, the surface has to be protected properly to avoid cracks and increased porosity of the surface. The cracks formation and increased porosity will reduce the strength and waterproofness and increase the risk of reinforcement corrosion caused by chloride migration and carbonation. 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 water and the cement.

In the first 10 maturity days (Mdays) the weight loss from the surface specimens was registered.The weight loss from those specimens cured with curing compound were compensated for the weight loss from the curing compound.

2.5. Testing of the Quality of the Concrete Surface

After the evaporation test the specimens were placed in a climate chamber with 20 °C, 65% RH and a wind velocity of app. zero until 28 maturity days. At 28 maturity days samples was taken from one half of each specimen for testing the quality of the concrete surface as shown in figure 4. The other half remained in the climate chamber.

Figure 4. Samples taken from the specimens.



A-C are samples for testing capillary water absorption, D is sample for testing carbonation, E-F are samples for testing chloride penetration and G-I are samples for testing micro cracks.

The quality of the concrete surface has been characterised based on the parameters described below.

Micro Cracks

By using test method TI-B 5 (87), three florescence impregnated thin sections, 30 x 45 mm, of each specimen has been analysed in microscope for amount of cracks, crack width, length and orientation and porosity evaluated by variation in water-cement ratio.

Chloride Penetration

By using test method ASTM C 1202 (91), two slices of each specimen have been tested for electrical resistance of the concrete expressed by Coulombs which pass through the specimen. The slices have a diameter of 100 mm and a thickness of 50 mm.

Capillary Water Absorption

By using test method TI-B 25, three samples, 90 x 130 mm, of each specimen has been tested for their ability to absorb water measured as a function of the square root of time. The samples had a thickness of 30 mm.

Carbonation
By using test method NT BUILD 357, one sample, 100 x 100 x 300 mm, of each specimen have been exposed to a concentration of CO_2 at 3.5 % and the carbonation depth will be measured 1, 2 and 3 months after start of exposure.

3. Test Results of the Curing Methods

In chapter 2 the plan for testing the fourteen different curing methods is given. In appendix A are given fifteen test reports; one of each curing method and one report on the curing compound. The test reports describes the concrete, curing methods and the measured weight loss.

3.1. Casting of Specimens

The concrete used for casting the specimens were delivered from a ready-mix plant in Copenhagen and transported to DTI, Taastrup where the specimens were cast. The transportation time was app. 1 hour. Each batch was on 3 m^3 concrete to prevent changes of the concrete as a result of the transportation. In figure 5 the equivalent water-cement ratio, air content and slump for the delivered concrete are shown. The equivalent water-cement ratio was stated on the batch report and the air content and slump were tested by DTI at delivery.

Figure 5. The delivered concrete (recipe no. 6021).

Variation in the delivered concrete

Specimen no.	Equivalent water-cement ratio	Air content [%]	Slump [mm]
1	0.37	5.7	100
2	0.37	5.7	100
3	0.38	5.8	140
4	0.39	6.7	80
5	0.38	7.0	130
6	0.38	7.0	130
7	0.38	6.7	90
8	0.38	6.7	90
9	0.39	6.5	120
10	0.39	6.7	80
11	0.39	6.1	90
12	0.39	6.1	90
13	0.39	6.5	90
14	0.39	6.5	90

Except for specimen no. 1, 2, 11 and 12 the specimens were cast by means of vibration table. It was chosen to cast specimens no. 1, 2, 11 and 12 by means of poker vibrator to avoid air bubbles on the surface.

3.2. Evaporation Tests

Immediately after casting the specimens were placed in the windtunnel thus the weight loss was recorded as soon as possible. The specimens for testing curing on free surface were placed horizontally on the weight in the windtunnel thus the surface was exposed to wind from the start. The specimens for testing the efficiency of mould curing were placed vertically on the weight in the windtunnel. At the time the surface of the specimens were demoulding the specimens was turn to a horizontal position and exposed to wind.

The climatic conditions under which the curing methods were tested are given as mean values in figure 6. The specimens are only exposed to wind, when the concrete surface is free or cured with curing compound. As specimen no. 3 only is in closen mould, the surface is not exposed to wind.

Figure 6. The climatic condition for the first 10 maturity days.

	Climatic Conditions		
Specimen no.	Temperature °C	Relative Humidity %	Wind Velocity m/s
1	22	63	3.6
2	22	63	3.6
3	20	67	-
4	20	67	3.6
5	20	66	3.6
6	20	66	3.6
7	20	44	3.6
8	20	44	3.6
9	20	67	3.6
10	20	67	3.5
11	20	68	3.7
12	20	68	3.7
13	20	67	3.6
14	20	67	3.6

3.3. Curing Methods

Figure 7. Actual curing methods.

			Surface		
Specimen no.	Mould Mh	Free surface Mh	Curing compound Mh	10 mm DOW-matt Mh	Wet surface Mh
1	1-76	76-240	-	-	-
2	1-77	77-79	79-240	-	-
3	1-240	-	-	-	-
4	-	2-240	-	-	-
5	1-25	25-240	-	-	-
6	1-25	25-27	27-240	-	-
7	-	1-240	-	-	-
8	1-78	78-80	80-240	-	-
9	-	1-5	5-240	-	-
10	-	2-5	-	-	5-244
11	1-25	25-27	-	27-240	-
12	1-77	77-79	-	79-240	-
13	-	1-5	-	5-240	-
14	-	1-2	2-240	-	-

In figure 7 are shown the actual curing methods. The period of each type of curing is given in maturity hours (Mh) after mixing.

The transportation time was app. 1 hour and the casting time was app. 1 hours.The evaporation tests were started app. 1 maturity hour (Mh) after mixing, due to the fact, that the concrete temperature is always under 20°C at delivery.

The specimen no. 9, 10 and 13 were cured after 5 Mh which is app. the setting time measured by the heat development as described in HETEK Control of Early Age Cracking, Phase 1.

3.4. Measured Weight Loss

To compare the weight loss from each type of curing the total weight loss is split into the 5 different curing types, which are shown in figure 8. The measured weight loss is compensated for the exaporation of the curing compound.

Figure 8. The weight loss from each curing types.

Specimen no.	Mould	Free surface	Curing compound	10 mm DOW-matt	Wet surface
	Total Weight Loss				
	kg/m^2	kg/m^2	kg/m^2	kg/m^2	kg/m^2
1	0.04	0.47	-	-	-
2	0.00	0.08	0.14	-	-
3	0.04	-	-	-	-
4	-	3.39	-	-	-
5	0.01	0.90	-	-	-
6	0.00	0.17	0.15	-	-
7	-	3.56	-	-	-
8	0.01	0.06	0.16	-	-
9	-	0.84	0.30	-	-
10	-	0.55	-	-	-1.22
11	0.03	0.23	-	0.01	-
12	0.01	0.06	-	0.01	-
13	-	0.60	-	0.06	-
14	-	0.14	0.20	-	-

For specimens no. 1, 3, 5, 8, 11 and 12 a weight loss was measured for the period with plywood on the surface. In theory the weight loss in this period should be zero but in practise it is very difficult to make a tight mould.

A weight loss was also measured when the surface was curing with a 10 mm DOW-matt on the surface as a results of evaporation along the border of the matt.

In figure 9 the weight loss is shown as a function of time for specimens cured in mould and after demoulding the surface was free until 240 maturity hours was reached.

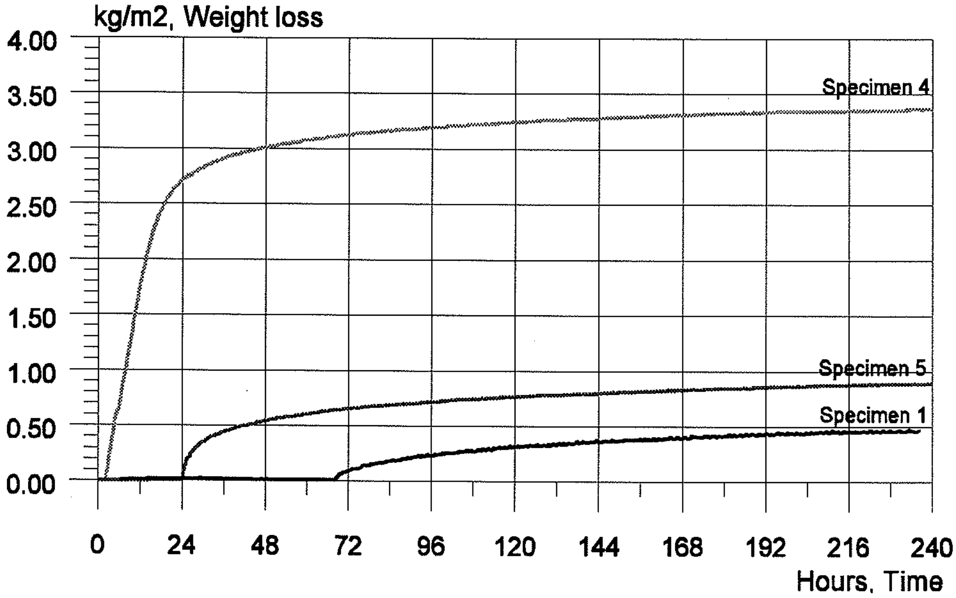


Figure 9. The weight loss for specimens with free surface.

Figure 10. The specimens listed after the weight loss.

Totale Weight Loss		
Specimen No.	Weight loss Kg/m^2	Curing Methods
10	-0.67	Water cured
3	0.04	Mould in 10 Mdays
12	0.08	Mould in 3 Mdays + DOW-matt
2	0.22	Mould in 3 Mdays + Curing compound
8	0.23	Mould in 3 Mdays + Curing compound - 50% RF
11	0.27	Mould in 1 Mday + DOW-matt
6	0.32	Mould in 1 Mday + Curing compound
14	0.34	Curing compound after 2 Mh
1	0.51	Mould in 3 Mdays
13	0.66	DOW-matt after 5 Mh
5	0.91	Mould in 1 Mday
9	1.14	Curing compound after 5 Mh
4	3.39	Free surface
7	3.56	Free surface - 50% RF

The total weight loss depends on the time and type of curing as shown in figure 10. As expected there is not a weight loss when the surface is cured with water and the weight loss is reduced the longer the concrete is in mould. As the DOW-matt is not tight the weight loss increase the longer time it is on the surface compared to the weight loss for concrete in mould. The weight loss is increased when there is used curing compound on the surface compared to the weight loss for concrete cured with DOW-matt and the weight loss increase the lower the relative humidity is.

Further test results shows that the weight loss from the surface cured with curing compound as soon as possible is less then the weight loss from the surface cured in mould for three maturity days.

4. Test Results of the Quality of the Concrete

The test results of each tests on the quality of the concrete surface are shown in the test reports, appendices B-E. All the test except capillary water absorption were at 28 maturity days which was the time the samples were cut out of the specimens. The samples were numbered after specimens which again referred to the curing method.

4.1. Microstructure and Microcracks

All the results of the microanalyses on the samples is given in appendix B. The results which concern the surface is given as follows.

Generally the specimens have not any coarse cracks and the air content is unchanged in the surface compared to the interior.

Specimen no. 8, 9 and 14 have a lower water-cement ratio (app. 0.30) in the surface while specimen no. 13 have a higher water-cement ratio (app. 0.55-0.60) in the surface. For specimen no. 14 there was not any aggregates larger than 0.5 mm in a depth of 20 mm from surface.

For the rest there was not any changes in the surface compared to the interior.

In figure 11 the amount of cracks and depth of carbonation is given as average: The cracks are split up in cracks perpendicular to the surface (⊥) and cracks parallel to the surface (=). The length of the surface is app. 44 mm.

Figure 11. Microanalyses

Depth of carbonation (C) and number of cracks						
Specimen no.	C mm	C along crack mm	Micro-crack ⊥ to surface	Micro-crack = to surface	Fine crack ⊥ to surface	Fine crack = to surface
1	0.4	2.1	4.3	0.0	0.0	0.0
2	0.5	2.1	5.3	0.0	0.0	0.0
3	0.5	3.2	2.7	0.0	0.0	1.0
4	4.0	0.0	3.0	5.3	0.0	0.3
5	1.7	0.0	0.7	0.0	0.0	0.0
6	0.3	2.2	5.3	0.0	0.7	0.0
7	3.6	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0
9	0.1	0.0	1.3	8.0	1.0	10.0
10	0.4	2.1	5.7	6.0	1.3	2.3
11	0.5	0.8	2.7	0.0	0.7	0.0
12	0.2	0.4	0.3	0.0	0.3	0.3
13	0.6	2.1	1.7	1.0	0.0	2.7
14	0.4	2.3	0.7	4.7	0.0	0.0

In figure 12 the amount of micro- and fine cracks to the surface are listed.

Figure 12. The specimens listed after the amounts of cracks.

Average of Cracks		
Specimen no.	Cracks	Curing methods
8	0.0	Mould in 3 Mdays + Curing compound - 50% RF
7	0.0	Free surface - 50% RF
5	0.7	Mould in 1 Mday
12	1.0	Mould in 3 Mdays + DOW-matt
11	3.3	Mould in 1 Mday + DOW-matt
3	3.7	Mould in 10 Mdays
1	4.3	Mould in 3 Mdays
13	5.3	DOW-matt after 5 Mh
14	5.3	Curing compound after 2 Mh
2	5.3	Mould in 3 Mdays + Curing compound
6	6.0	Mould in 1 Mday + Curing compound
4	8.7	Free surface
10	15.3	Water cured
9	20.3	Curing compound after 5 Mh

4.2. Chloride Penetration

All the results of the chloride penetration on the samples are given in appendix C. The average of the chloride penetration is shown in figure 13 where the specimens are listed after the amount of chloride penetration.

Figure 13. The specimens listed after the chloride penetration.

Chloride Penetration		
Specimen no.	Chloride penetration [Coulombs]	Curing methods
8	951	Mould in 3 Mdays + Curing compound - 50% RF
10	983	Water cured
14	985	Curing compound after 2 Mh
1	1013	Mould in 3 Mdays
2	1049	Mould in 3 Mdays + Curing compound
12	1059	Mould in 3 Mdays + DOW-matt
11	1084	Mould in 1 Mday + DOW-matt
13	1463	DOW-matt after 5 Mh
6	1556	Mould in 1 Mday + Curing compound
9	1710	Curing compound after 5 Mh
5	1717	Mould in 1 Mday
3	2239	Mould in 10 Mdays
4	>4000	Free surface
7	>4000	Free surface - 50% RF

4.3. Capillary Water Absorption

Figure 14. Test Results.

TI-B 25				
Specimen no.	Porosity [vol-%]	Degree of saturation start	Degree of saturation	Period of saturation [Hours]
1	15.7	0.04	0.61	5.6
2	15.1	0.03	0.63	8.1
3	14.5	0.15	0.53	4.0
4	18.7	0.07	0.48	5.3
5	16.0	0.14	0.41	3.5
6	16.9	0.15	0.42	3.2
7	15.9	0.13	0.40	7.3
8	14.7	0.31	0.44	17.6
9	18.8	0.29	0.41	6.6
10	16.7	0.28	0.54	2.3
11	14.5	0.29	0.61	3.6
12	14.1	0.34	0.56	3.4
13	16.3	0.21	0.50	4.0
14	15.8	0.28	0.43	15.2

All the results of the capillary water absorption on the samples are given in appendix D. The results are shown in figure 14. Samples from specimen no 1 to 3 were first dried 6 week after casting.

Test method, TI-B 25, prescribing that the samples are dried at 50 °C for minimum 2 days before testing. The period for drying was chosen to app. 1 week which results in very different degrees of saturation at the start of testing as shown in figure 14. The degree of saturation have influence on the speed of saturation which makes it difficult to analyse the test results.

It was chosen not to list the curing methods after the test result as the curing methods can be listed after porosity, degree of saturation or period of saturation. In figure 15 is shown the capillary water saturation as a function of square time for samples from specimen no. 1 and 14. By using linear regression on the start and the end of the test period the degree of saturation and time of saturation was determined.

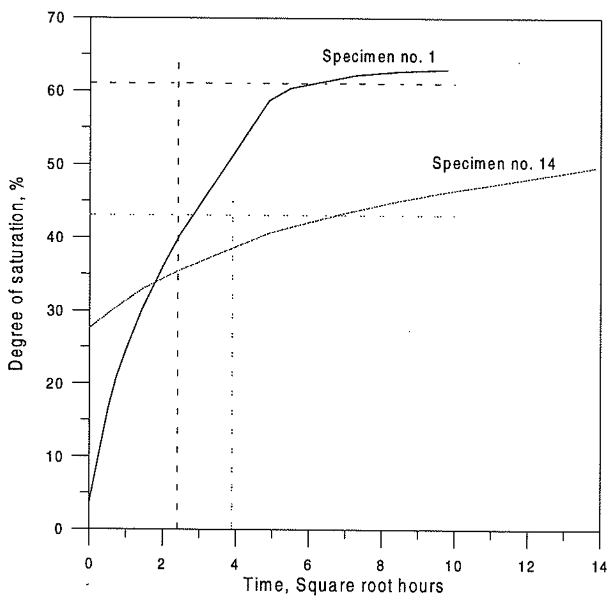


Figure 15. Capillary Water Absorption.

4.4. Carbonation

All the results of the carbonation depth of the samples are given in appendix E. In figure 16 the depth of surface carbonation is given as a average depth, d_k, and a maximum depth, d_{max} after 1,2 and 3 months of exposure. As the temperature in a period is app. 21°C, 1 month is app. 1 maturity month.

As shown in figure 16 the maximum depth of surface carbonation can be lower in time caused by the fact that the depth of carbonation is measured on different parts of the sample after 1, 2 and 3 month of exposure.

In figure 17 the specimens are listed after the carbonation depth.

Figure 16. The depth of surface carbonation.

Depth of Surface Carbonation in mm						
Specimen No.	1 month d_k	1 month d_{max}	2 month d_k	2 month d_{max}	3 month d_k	3 month d_{max}
1	0	0	3	4	3	5
2	0	0	3	3	3	5
3	6	9	9	10	10	12
4	16	19	20	23	25	26
5	7	8	9	11	11	13
6	4	5	6	8	8	9
7	14	17	21	25	22	25
8	0	0	0	0	0	3
9	4	6	4	6	8	10
10	3	5	5	11	5	7
11	5	7	7	11	8	10
12	3	6	4	6	5	9
13	3	5	3	4	3	4
14	0	0	0	2	0	0

Figure 17. Specimens listed after carbonation depth.

Average Carbonation Depth after 3 Month		
Specimen No.	Carbonation Depth [mm]	Curing Methods
14	0	Curing compound after 2 Mh
8	0	Mould in 3 Mdays + Curing compound - 50% RF
13	3	DOW-matt after 5 Mh
2	3	Mould in 3 Mdays + Curing compound
1	3	Mould in 3 Mdays
10	5	Water cured
12	5	Mould in 3 Mdays + DOW-matt
6	8	Mould in 1 Mday + Curing compound
9	8	Curing compound after 5 Mh
11	8	Mould in 1 Mday + DOW-matt
3	10	Mould in 10 Mdays
5	11	Mould in 1 Mday
7	22	Free surface - 50% RF
4	25	Free surface

5. Summery of the Test Results

In figure 18 is given a summery of the quality of the concrete surface expressed by different test methods. The test results are listed such as no. 1 is the best result and no. 14 is the poorest results.

Figure 18. Test Results

	Quality of the Concrete Surface				
Curing Methods	Weight Loss	Cracks	Chloride Penetration	Period of Satura-tion	Average carbonation depth after 3 month
Mould 3 MD	8	7	4	6	3
Mould 3 MD + C	4	8	5	3	3
Mould 10 MD	2	6	12	8	11
Free	13	12	13	7	14
Mould 1 MD	10	3	11	11	12
Mould 1 MD +C	11	11	9	13	8
Free *	14	1	13	4	13
Mould 3 MD + C *	5	1	1	1	1
C after 5 Mh	12	14	10	5	8
Water	1	13	2	14	6
Mould 1 MD + DOW	6	5	7	10	8
Mould 3 MD + DOW	3	4	6	12	6
Dow after 5 Mh	9	8	8	8	3
C after 2 Mh	7	8	3	2	1

6. Follow-up

As described in chapter 2.5 the other half of the specimens which was not tested remain in the climate chamber at 20 °C and 65 % relative humidity. All specimens were cast from February to June. The 4. July 1996 were all the other half of the specimens removed outside to the field test area at DTI, Taastrup thus the specimens are exposed to Danish environmental conditions. Thereby it will be possible to make test later on of the quality of the different curing methods.

The evaluation of all the obtained test results are a part of phase 2 - Evaluation of Obtained Test Results and Establishment of Theory.

7. List of Literature

Berrig, A. and Frederiksen, J.O.: "Måling af betonforseglingsmidlers virkningsgrad, Ny prøvningsmetode; TI-B 33" (in Danish, Determination of the efficiency of concrete curing compounds, New test method: TI-B 33). DTI report, November 1992.

Haugaard, M. and Berrig, A.: "HETEK-Curing-Supplementary research-Proposal". Road Directorate Report No. 38, Copenhagen 1996.

Riis, K. and Haugaard, M.: "Appendices to HETEK-Curing-Phase 1: Laboratory Tests". Copenhagen 1996. Can be required at Road Directorate or at DTI and included following appendices:

Appendix A:	Test Reports on the Evaporation Test
Appendix B:	Test Reports on the Microstructure
Appendix C:	Test Reports on the Chloride Penetration
Appendix D:	Test Reports on the Capillary Water Absorption
Appendix E:	Test Report on the Carbonation