HETEK

Curing
Phase 3: Verification 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.

Part 6 is divided in a state of the art, a supplementary research, phase 1 to 4, main report and guidelines. Phase 3: Verification Tests describing four curing methods tested in DTI's laboratory and six curing methods tested in the field.

The field tests were performed on a bridge construction. To verify the actual obtained climatic conditions in the field a mini-weather station was placed near by the tested concrete surface. The mini-weather station measured continuously the temperatures in the air, wind velocity, direction of the wind, relative humidity and daily rain fall in the test period.

The first two curing methods in the laboratory were performed with the same concrete recipe as in phase 1 and is a supplement to phase 1. The two other curing methods in the laboratory were performed with the same concrete recipe as used in the field tests. In DTI's laboratory it was possible to expose the concrete surface to a controlled temperature, relative humidity and wind velocity. At the same time the concrete specimen was weighed continuously and evaporated amount of water from the conrete surface was calculated.

For all curing methods the quality of the concrete surface were expressed on testing of the parameters microstructure 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 seven parts within the following subjects:

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

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

This project regarding curing is performed by:

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The 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.

February 1997
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Steering Committee of HETEK-Curing project

1. Introduction

With reference to HETEK - Curing - Phase 2: Evaluation of Test Results [Tommy Nielsen, 1997], testing of 4 curing methods in laboratory and 6 curing methods in field are described in this report. These tests form part of the background for preparing guidelines on 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 practice 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 today's 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 testing in phase 3 is to veryfy the results from phase 1 and the conclusions from phase 2 based on phase 1. This 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 consists of a laboratory test of 14 different curing methods. The 14 different curing methods were chosen on the contractors experience which again are based on how practical and economical the curing methods are. They include frequently used curing methods and also some extreme methods such as water curing and no protection. Each curing method was performed on a concrete specimen that after casting was placed in such a way that it was possible to expose the concrete surface to a controlled temperature, relative humidity and wind velocity. At the same time the concrete specimen was weighed continuously in a period of 10 maturity days from the time of mixing the concrete and the evaporated amount of water from the concrete surface was calculated. At the age of 28 maturity days the quality of the concrete surface was tested by different test methods.

The obtained test results were evaluated in phase 2 of HETEK - Curing and some of the curing methods were suggested to be investigated further. Below is a description of the verification tests performed in phase 3.

2.1 Test Programme in Laboratory

The test programme in DTI's laboratory is described in figure 1.

Figure 1. Test programme in laboratory

		Surface		
Test No.	Plywood formwork Mh	Free surface Mh	Curing compound Mh	Plastic Mh
15	0-72	72-74	74-240	-
16	-	0-2	2-240	-
17	0-72	72-74	74-240	-
18	-	-	-	0-240

All tests are cured in a period of 10 maturity days as described above.

Test No. 15 and 16 is performed with concrete recipe No. 6021 from 4K, appendix 1. The recipe is the same as used in phase 3. The climatic conditions are 3.6 m/s, 20 °C and 50 % RH.

Test No. 17 and 18 is performed with concrete recipe No. A35LSFAA25L3 from Unicon, appendix 1. The recipe is the same as used in the field test, see chapter 2.2. The climatic conditions are 3.6 m/s, 20 °C and 70 % RH.

Afterwards the specimens are placed in a climate chamber at 20 °C and 65 % RH until 28 maturity days are reached.

2.2 Test Programme in the Field

In the field six curing methods were performed on the foundation of a bridge construction which were cast with concrete recipe A35LSFAA25L3 from Unicon, appendix 1. The concrete recipe from Unicon was chosen by the contractors but is similar to the concrete recipe from 4K. The six curing methods are as follows and they are marked horizontal or vertical according to location on the foundation.

Test 1 - Horizontal:	Transparent plastic on the concrete surface as soon as possible.
Test 2 - Horizontal:	Curing compound on the fresh, wet concrete surface.
Test 3 - Horizontal:	Curing compound on the concrete surface at the time where the concrete begins to harden.
Test 1 - Vertical:	Formliner on the concrete surface in the first 3 maturity days and curing compound on the concrete surface after demoulding.
Test 2 - Vertical:	Plywood formwork on the concrete surface in the first 3 maturity days and curing compound on the concrete surface after demoulding.
Test 3 - Vertical:	Timber formwork on the concrete surface in the first 3 maturity days and curing compound on the concrete surface after demoulding.

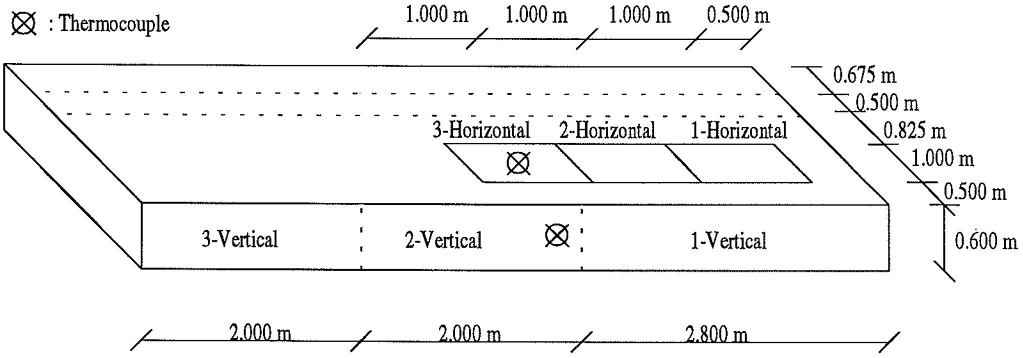

Figure 2. Drawing of the foundation

The climate conditions in the field test period were measured with instrumens which are a part of mini-weather station. Further the temperature in the concrete are measured by thermocouples thus the maturity can be calculated.

2.3 Testing of the Quality of the Concrete Surface

At 28 maturity days samples were taken from the concrete surface for testing of the quality.

The location of samples taken from specimen No. 15 and 16 are shown on figure 3.

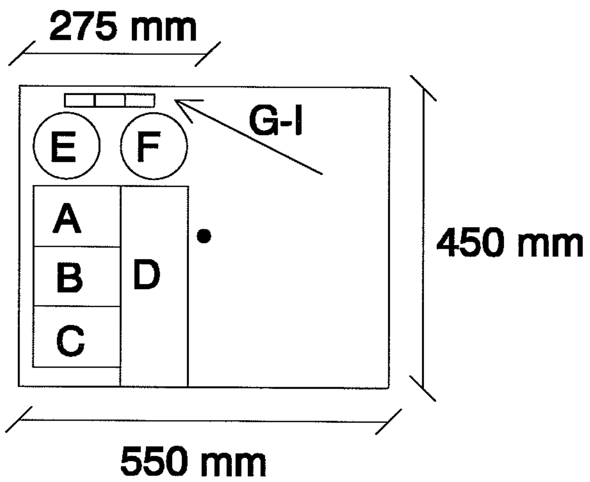

Figure 3. Samples taken from the specimen No. 15 and 16

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 microcracks.

The number of samples from specimen No. 17 and 18 were reduced to only A, D, F and G because the standard deviation of the test results are very small. The location of samples taken from specimen No. 17 and 18 are shown on figure 4.

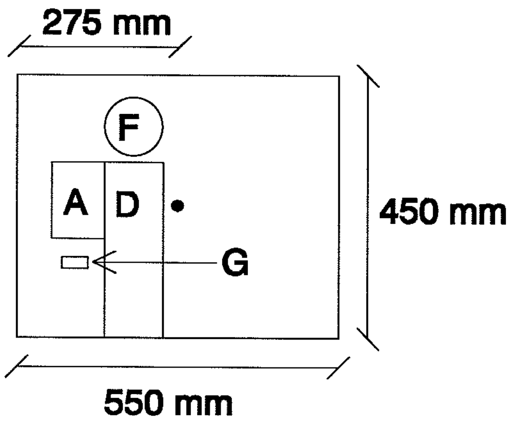

Figure 4. Samples taken from the specimen No. 17 and 18.

The other half of specimen No. 15 to 18 were removed to the outdoor field test area at DTI, Taastrup.

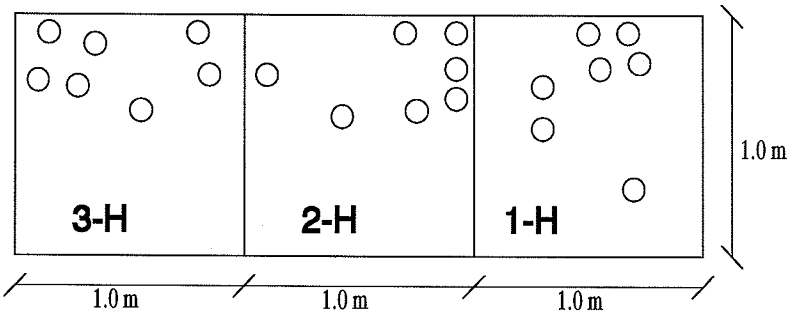

Figure 5. 7 samples taken from each horizontal curing field cured as described above.

In the field 7 samples with a diameter of 100 mm were taken from each curing field after approx 12 maturity days. Figure 5 show the location of the samples taken from the horizontal surface. The samples from the vertical surface were taken approx 0.40 m from the ground and 0.10 m from the top in a line. The samples were laid in plastic bags and transported to the laboratory where they were stored at approx 20 °C until they were 28 maturity days old. The samples were not marked because the samples had been taken as near to each other as possible.

Four of the samples were used for testing the quality of the concrete surface. The other three were removed to the field test area where the other half of the specimens tested in laboratory are placed.

The quality of the concrete surface is characterised based on the parameters de-scribed below.

Micro Cracks

By using test method TI-B 5 (87), fluorescence impregnated thin sections, 30 x 45 mm, 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), the slices 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, samples of 90 x 130 mm, have been tested for their ability to absorb water measured as a function of the square root of time. The samples have a thickness of 30 mm.

Carbonation

By using test method NT BUILD 357, one sample, 100 x 100 x 300 mm, of each specimen has 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. Laboratory Tests

In chapter 2.1 the plan for the laboratory tests is given. Appendix A contains four test reports; one on each curing method. The test reports describe the concrete used for casting the specimen, the curing methods on the specimens and the evaporated amounts of water from each specimen. In appendix B the test report on concrete curing compound is given.

3.1 Casting of Specimens

The concrete used for casting specimen No. 15 and 16 was delivered from 4K's ready-mix plant in Ejby and transported to DTI, Taastrup where the specimens were cast. The concrete recipe was No. 6021 which is the same recipe as used in phase 1. The transportation time was approx 30 minutes. The batch consisted of 3 m^3 concrete to prevent changes of the concrete as a results of the transportation. In figure 6 the batch report for the concrete is given.

The concrete used for casting specimen No. 17 and 18 was delivered from Unicon's ready-mix plant in Avedøre and transported to DTI, Taastrup where the specimens were cast. The concrete recipe was No. A35LSFAA25L3 which is the same recipe as used in the field tests. In the field tests the concrete was delivered from Unicon's ready-mix plant in Copenhagen which also delivers concrete after recipe No. A35LSFAA25L3. The transportation time from the ready-mix plant in Avedøre to DTI, Taastrup was approx 45 minutes. It was chosen only to order a batch of 1 m^3 which is evaluated to be enough to prevent changes of the concrete as a results of the transportation. In figure 6 the batch report for the concrete is given. Further 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. The concrete constains low-alkali sulphateresistant cement, fly ash, silica fume, seasand, granite and entrained air.

Figure 6. Concrete recipe No. 6021 from 4K-Beton and concrete recipe No. A35LSFAA25L3 from Unicon.

Concrete recipe:		4K	Unicon
	Type/origin/class	kg/m^3	kg/m^3
Cement	Low-alkali Sulphateresistant CEM I 42,5(HS/EA/≤2)	283	269
Fly ash	Danaske	61	62
Silica fume	Slurry or Silica fume	12	15
Water	Water	127	134
Fine aggregate	RN, Avedøre sand 0/4, SA	731	748
Coarse aggregate	Rønne granit 4/16,A	-	674
Coarse aggregate	Rønne granite 8/16, A	531	-
Coarse aggregate	Rønne granite 16/25, A	550	448
Air entrainment	Conplast 316 AEA, Fosroc 1:1	0.404	-
Air entrainment	Conplast 316 AEA, Fosroc 1:5	-	1.74
Plasticizer	Conplast 212, Fosroc	1.406	1.14
Superplasticizer	Peramin F, Fosroc	2.752	1.84
Equivalent water-cement ratio		0.39	0.42
Air content at delivery (volume)		4.7 %	4.4 %
Slump at delivery		70 mm	55 mm

The four specimens were cast in moulds of plexiglass with a surface of 450 x 550 mm and a thickness of 100 mm. Specimen No. 15 and 17 were cast against a plywood plate which was placed on the plexiglass mould. Specimen No. 16 and 18 were cast with free surface.

Immediately after casting the specimens were placed in the test set-up and the evaporation test began.

3.2 Evaporation Tests

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 specimens were moved to the windtunnel placed in a climate chamber where the temperature and the relative humidity are kept approximately constant. Figure 7 shows one of the windtunnels. The temperature in the climate cabinet was measured by using a thermocouple (copper/constantan) which was placed in the middle of the climate chamber. The humidity was automatically controlled and measured.

Each specimen was placed on a scale in the windtunnel and the weight was recorded continuously from approx 1 maturity hour after mixing. The surface of specimen No. 16 was exposed to a well defined laminar air flow immediately while the surface of specimen No. 15 and 17 were exposed to a well defined laminar air flow after demoulding. The wind was established by means of a ventilator which absorb air through the tunnel and measured by a Therm rotor anemometer. The anemometer was placed in the middle of the wind tunnel 30 mm above the free surface of the specimens. Specimen No. 18 was covered with plastic in the test period and was not exposed to wind.

Further the temperature in the specimens were measured by using a thermocouple cast in the center of each specimen.

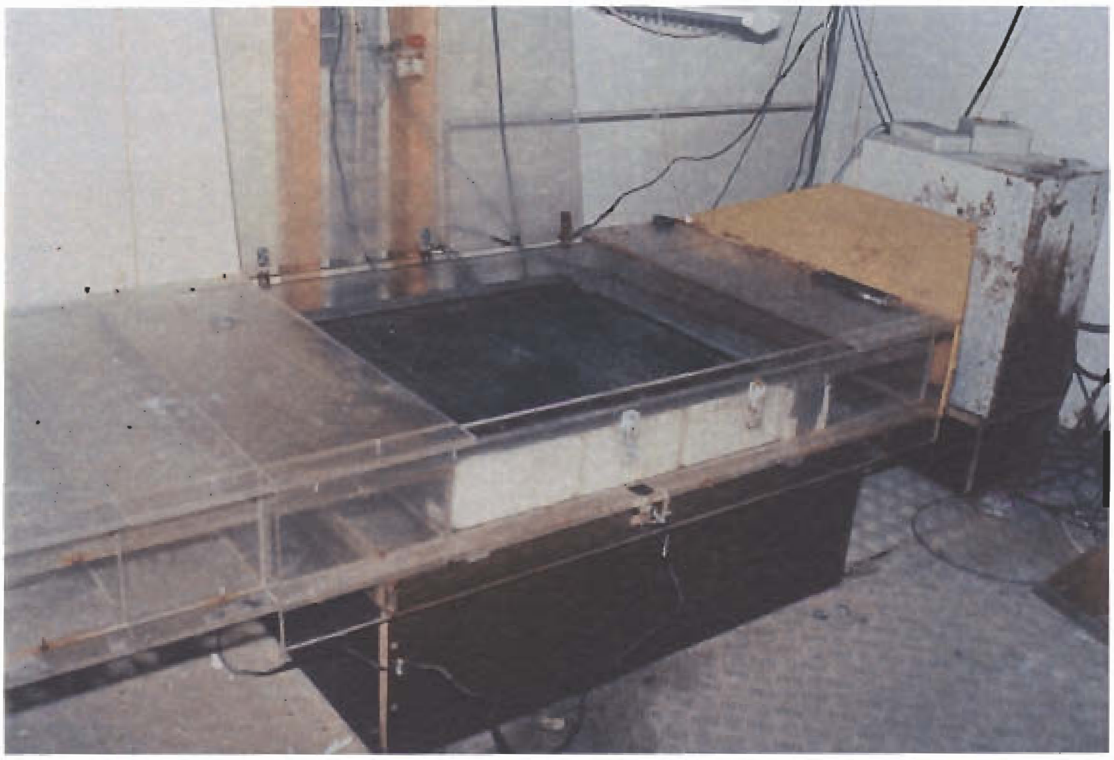

Figure 7. Photo of the windtunnel

At an age of 10 maturity days the specimens were removed to a climate chamber where the climate conditions are continuously 20 °C, 65 % relative humidity and a wind velocity of nearly zero m/s.

3.3 Curing Methods

In figure 8 the actual curing methods are shown. The period of each type of curing is given in maturity hours (Mh) after mixing.

Figure 8. Actual curing methods

	Surface			
Specimen No.	Plywood Mh	Free surface Mh	Plastic Mh	Curing compound Mh
15	1-81	81-83	-	83-240
16	-	1-2	-	2-240
17	2-75	75-77	-	77-241
18	-	-	2-243	-

Specimen No. 15 and 16 were cured at 21 °C, 50 % RH. The wind velocity was respectively 3.62 m/s for specimen No. 15 and 3.57 m/s for specimen No. 16. Specimen No. 17 and 18 were cured at 20 °C, 69 % RH. The wind velocity was 3.58 m/s for specimen No. 17.

3.4 Measured Weight Loss

In the first 10 maturity days the weight loss from the specimen surface was registered. The measured weight loss was substracted the water evaporated from the curing compound, thus the stated weight loss expresses the water evaporated from the surface of the specimen. To compare the weight loss from each type of curing the total weight loss is split into the 4 different curing types, which are shown in figure 9.

Figure 9. The weight loss from each curing type.

	Total Weight Loss			
Specimen No.	Plywood kg/m^2	Free surface kg/m^2	Plastic kg/m^2	Curing compound kg/m^2
15	0.03	0.07	-	0.15
16	-	0.26	-	0.36
17	0.00	0.12	-	0.18
18	-	-	0.05	-

In theory the weight loss for the period with plywood formwork or plastic on the surface should be zero but in practice it is very difficult to produce a tight mould or to cover the surface tightly.

3.5 Tests Results of the Quality of the Concrete Surface

The results of each test on the quality of the concrete surface are shown in the test reports, appendix C to F. All tests except capillary water absorption were performed at 28 maturity days at which time the samples were cut from the specimens.

Microstructure and Microcracks

All results of the microanalyses on the samples are given in appendix B. The results which concern the surface are as follows. No remarks on concrete composition and concrete homogeneity. No coarse cracks are found in the specimens. Both capillary porosity and air content are unchanged in the surface for all specimens except for specimen No. 16 where the water-cement ratio is lower (approx 0.30) in a zone from 0.5 mm to 1.5 mm below the surface.

Figure 10 states the amount of cracks and depth of carbonation. As there are 3 samples from specimen No. 15 and 16 the results are given as an average. The cracks are split up into cracks perpendicular to the surface (⊥) and cracks parallel to the surface (=). The length of the surface is approx 44 mm.

Figure 10. Microstructure and -cracks.

Depth of carbonation (C) and number of cracks in the surface (outmost 2.5 mm)

Specimen No.	C mm	C along crack mm	Micro-crack ⊥ on surface	Micro-crack = on surface	Fine crack ⊥ on surface	Fine crack = on surface
15	0.7	2.4	4.7	0.0	0.3	0.0
16	0.0	0.0	0.3	6.7	0.0	0.0
17	0.6	3.2	4	0	0	0
18	1.5	3.3	7	1	1	0

Totale amount of cracks in the whole thin section:

Specimen No. 15:	Fine cracks: 0.3 Micro cracks: 4.7 Crack length : 0.2 mm to 5.0 mm Total crack length: 8.6 mm
Specimen No. 16:	Fine cracks: 0.0 Micro cracks: 7.0 Crack length : 0.2 mm to 2.1 mm Total crack length: 6.2 mm
Specimen No. 17:	Fine cracks: 0 Micro cracks: 4 Crack length : 0.2 mm to 4.5 mm Total crack length: 9.9 mm
Specimen No. 18:	Fine cracks: 1 Micro cracks: 8 Crack length : 0.4 mm to 4.7 mm Total crack length: 12.2 mm

Chloride Penetration

The results of the chloride penetration are given in appendix D. Figure 11 states the chloride penetration. As there are 2 samples from specimen No. 15 and 16 the results are given as average.

Figure 11. Chloride Penetration

ASTM C 1202	
Specimen No.	Chloride penetration [Coulombs]
15	1098
16	1015
17	1534
18	1360

Capillary Water Absorption

Test method TI-B 25 prescribes that samples are dried at 50 °C for minimum 2 days before testing. A drying period of about 1 week was chosen which results in very different degrees of saturation at the start of testing as shown in figure 12. The degree of saturation influence the speed of saturation.

The test reports are given in appendix E. They show that the tests were started at 35 maturity days for specimen No. 15 and 16 and at 63 maturity days for specimen No. 17 and 18. As there are 3 samples from specimen No. 15 and 16 the results are given as average.

Figure 12. Capillary water absorption

TI-B 25				
Specimen No.	Porosity [vol-%]	Degree of saturation start	Degree of saturation	Period of saturation [Hours]
15	13.5	0.38	0.51	2.8
16	14.2	0.37	0.52	3.2
17	16.7	0.30	0.58	9.3
18	17.4	0.24	0.71	1.6

Carbonation

The test reports are given in appendix F. Figure 13 states test results as follows: They are the depth of surface carbonation as an 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 approx 21°C, 1 month is approx 1 maturity month.

Figure 13. Test results from test method NT Build 357

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}
15	0	0	0	5	0	7
16	0	3	0	4	0	3
17	3	5	5	11	7	12
18	12	17	17	19	20	24

4. Curing Tests in the Field

In chapter 2.2 the plan for testing 6 different curing methods is given. Each curing method gives different patterns on the concrete surface. Therefore, it was decided to perform the curing tests on the foundation part of a bridge construction. The section was offered by RASTON, contractor.

Figure 14 shows the position of thermocouples and the 6 different test fields. The thermocouples are placed 10 mm from the concrete surface. Each test field marked Horizontal is 1 m^2. The test fields marked 1-Vertical is approx 1.7 m^2 and 2- and 3-Vertical are 1.2 m^2.

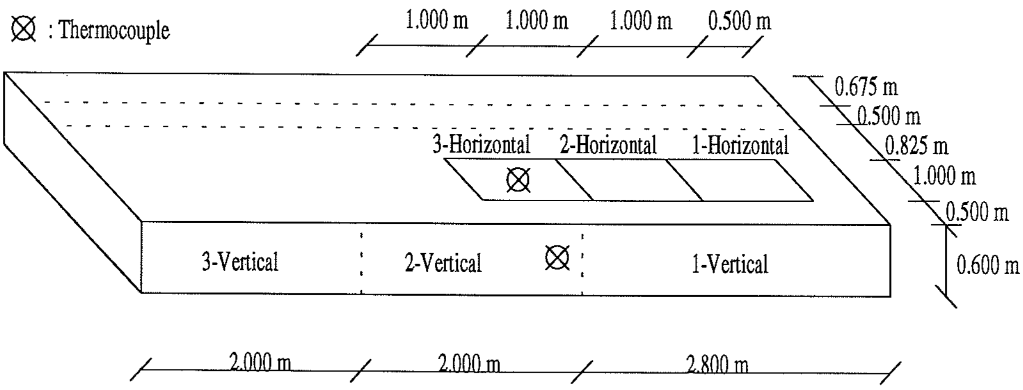

Figure 14. Drawing of the foundation

Figure 15 shows the actual curing tests on the 6 test fields.

Figure 15. The curing tests on the 6 test fields

Field	Formwork Mh	Free surface Mh	Curing compound Mh	Plastic Mh	Exposed to rain Mh
1-Horizontal	-	-	-	1-210	210-297
2-Horizontal	-	-	1-297	(20-88)	119-297
3-Horizontal	-	1-7	7-297	(20-88)	119-297
1-Vertical	1-79	79-284	-	(98-113)	79-284
2-Vertical	1-79	79-80	80-284	(98-113)	79-284
3-Vertical	1-79	79-80	80-284	(98-113)	79-284

Field marked 1-Horizontal has been exposed to 26.8 mm rain. Field marked 2- and 3-Horizontal have been exposed to 35.2 mm rain. Field marked Vertical have been exposed to 45.8 mm rain. The mean wind velocity in the air was 1.2 m/s and the mean relative humidity was 87 %.

Field marked 1-Vertical has been protected with formliner.
Field marked 2-Vertical has been protected with plywood formwork.
Field marked 3-Vertical has been protected with timber formwork.

The periods marked with () and the period, where the concrete surface was exposed to rain, were not planed.

Appendix G contains the temperature measured with thermocouples and calculated maturity for the fields marked Horizontal and Vertical.

Appendix H contains two heat development reports on the concrete. From the reports it appears that the setting time is approx 4-6 maturity hours. It is determined as τ_0. Field marked 3-Horizontal was treated with curing compound after 7 maturity hours which was estimated to be the setting time as the surface become mat dry (disappearing of bleeding-water).

4.1 Casting the Foundation

The concrete used for casting the foundation was delivered Thursday, 24th October 1996, from Unicon's ready-mix plant in Copenhagen and transported to the building area at Kastrup where the foundation was cast. For casting 19 m^3 concrete (recipe No. A35LSFAA25L3 from Unicon) was ordered. The concrete was delivered in 3 batches. In appendix G is given the required concrete together with the three batch reports. In figure 16 the last two batch reports are given as the concrete for the 3 test fields marked Vertical were cast with concrete from the second batch and the 3 test fields marked Horizontal were cast with concrete from the third batch.

Figure 16. Concrete batch report on the second and third batch

Mixed after recipe No. A35LSFAA25L3 from Unicon		2. batch	3. batch
	Type/origin/class	kg/m^3	kg/m^3
Cement	Low-alkali Sulphate CEM I 42,5(HS/EA/≤2)	277	276
Fly ash	Danaske	63	63
Silica fume	Elkem	16	16
Water	Water	139	140
Fine aggregate	RN, Avedøre sand 0/4, SA	718	719
Coarse aggregate	Dalby granite 4/16, A	677	673
Coarse aggregate	Dalby granite 16/25, A	451	452
Air entrainment	Conplast 316 AEA, Fosroc 1:5	1.35	1.34
Plasticizer	Conplast 212, Fosroc	1.67	1.64
Superplasticizer	Peramin F, Fosroc	1.88	1.88

Equivalent water-cement ratio Design air content was 5 vol-% and design slump was 140 mm	0.42

The foundation was cast from 1:30 pm to 4:20 pm. The concrete had an age of approx 1 maturity hours when the concrete was cast. Figure 17 show the casting process where the concrete was placed in the mould and vibrated by use of poker vibrator.

Figure 17. The concrete was placed in the mould by use of a buggy

After the last concrete was placed in the mould and vibrated at 16:20 pm, the surface was smoothed and glazed.

4.2 Curing of the Test Fields

Below is a log-book describing the actuel performed curing tests. This is summed in figure 15, page 14.

Thursday, 24th October 1996:
At 4:40 pm plastic was laid on test field marked 1-Horizontal to reduce water evaporation. The two test fields marked 2-Horizontal and 3-Horizontal were not covered with plastic.

At 5:00 pm curing compound was spayed on field marked 2-Horizontal. The container was weighed before and after the curing compound was sprayed on the field. The difference was 800 gram. DTI assume the weight of curing compound on the field is between 400 gram and 480 gram as the container with curing compound was not tight and some test sprayed were included in the weight.

At 5:10 pm a shelter was established over the 3 fields marked Horizontal. The distance between the shelter and surface of the 3 curing fields was from 250 mm to 600 mm. The shelter was established to protect the concrete surface from rain. Figure 18 the 3 test fields marked Horizontal after the shelter was established is shown.

At 11:35 pm 480 gram of curing compound was sprayed on the surface marked 3-Horizontal. A new tight container with curing compound was used. The weight of the container, before and after the curing compound was sprayed on the surface, was assumed to be exactly the amount of curing compound on the surface of field marked 3-Horizontal. According to the producer the required quantity of curing compound is 233 gram/m^2.

Figure 18. The 3 curing fields marked Horizontal were protected from rain by a shelter.

Friday, 25th October 1996:
At approx 11:00 am plastic was laid on the fields marked 2-Horizontal and 3-Horizontal as the surface around the reinforcing rods to the wall was cleaned by sandblasting. By a mistake the plastic was not removed afterward.

Sunday, 27th October 1996:
At 2:20 pm the plastic was removed from the fields marked 2-Horizontal and 3-Horizontal.

At 2:40 pm the mould was removed and the surface of the fields marked Vertical were free.

At 3:45 pm the fields marked 2-Vertical and 3-Vertical were cured with curing compound. 1310 gram of curing compound was sprayed on the concrete surface of the fields cast against plywood or timber formwork ie. an area of approx 2.4 m^2. As most of the curing compound run off the fields marked 2- and 3-Vertical, it was assumed that the field was cured with approx 200 gram/m^2 curing compound.

Monday, 28th October 1996:
Between 3:00 and 3:30 pm the shelter and the plastic on field marked 1-Horizontal were removed while the sand from sandblasting was removed. Afterwards the plastic was replaced on the field marked 1-Horizontal and the fields marked Vertical but the shelter was not reestablished again. Therefore the fields marked 2-Horizontal and 3-Horizontal were exposed to rain. It rained from 11:00 pm the same day.

Tuesday, 29th October 1996:
At 11:30 am the plastic on fields marked Vertical was removed.

Monday, 4th November 1996:
The plastic was removed from field marked 1-Horizontal as shown in figure 19. According to information received on the building site the plastic has been on the field until this morning. Further the figure show the concrete surface after being cured with either plywood, timber formwork or formliner.

4.3 Taking of Samples

Wednesday, 13th November 1996:
7 samples from each field marked Horizontal were drilled and transported in plastic bags to DTI's laboratory where they remained in the plastic bags until testing.

Thursday, 14th November 1996:
7 samples from each field marked Vertical were taken and transported in plastic bags to DTI's laboratory where they remained in the plastic bags until testing. Figure 20 shows a photo of the foundation after some of the samples had been taken.

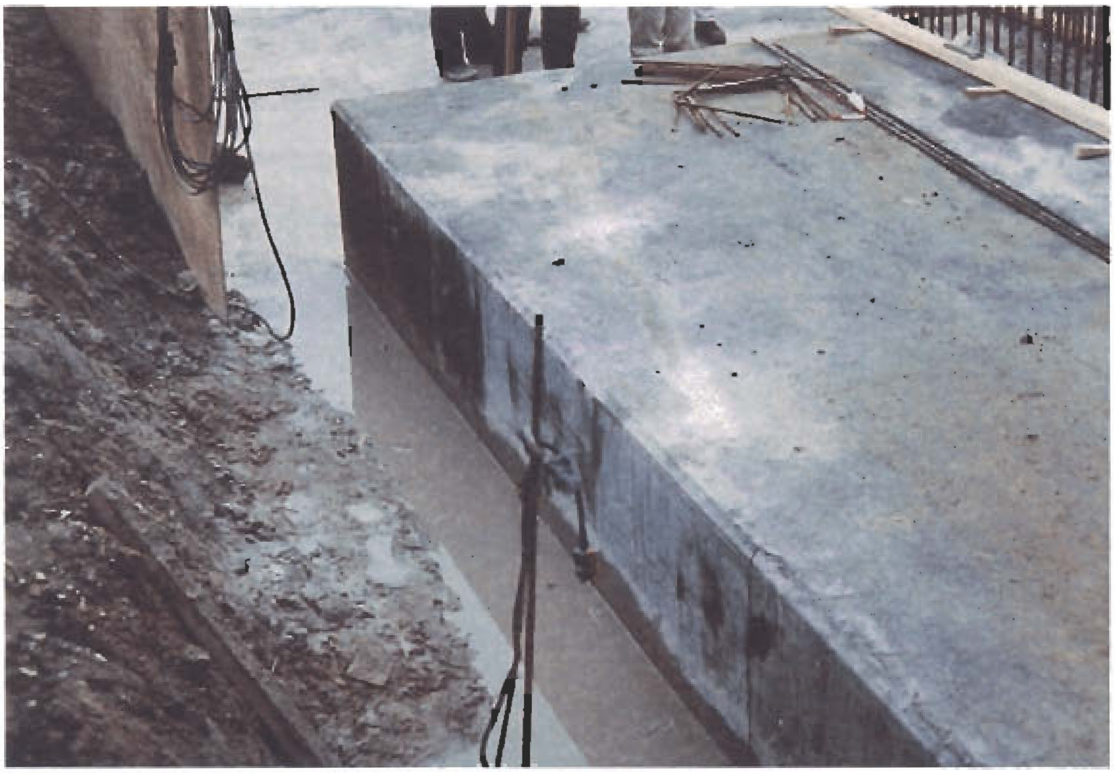

Figure 19. The foundation after removal of mould, plastic and shelter were removed.

Figure 20. The foundation after some of the samples had been taken.

Thursday, 28th November 1996:
The samples had an age of approx 28 maturity days and 4 of the samples were used for testing on the concrete surface.

4.4 Mini-weather station

The mini-weather station measured continuously the temperature in the air, wind velocity, direction of the wind, relative humidity and daily rain fall in the test period.

Figure 21 shows a photo of the rain gauge on the wall and the anemometer which registers velocity and direction of the wind. The relative humidity and the temperature in the air were measured with a little box placed near the foundation. By using a data logger the climate condition was measured continuously every 30 minutes.

Figure 21. The rain gauge and the anemometer from the mini-weather station.

In appendix G is given all climate conditions during the period from casting to sample taking from the fields. Figure 22 shows the relative humidity and temperature in the air during the test period. The mean relative humidity was 87 %.

In figure 23 the measured rain fall and wind velocity are stated. The mean wind velocity of the air is 1.2 m/s. This is measured at a height of approx 6 m above the surface of the foundation.

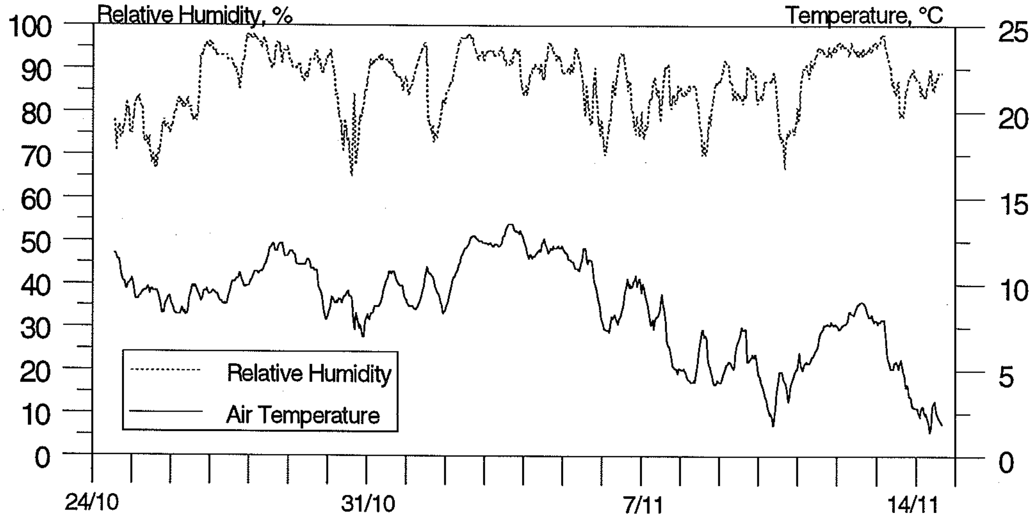

Figure 22. Measured relative humidity and temperature in the air.

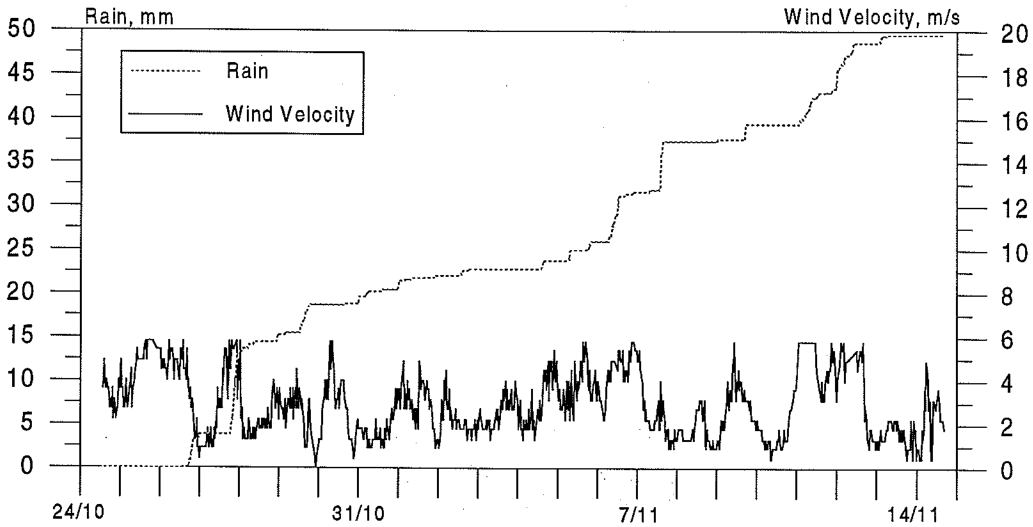

Figure 23. Measured rain and wind velocity

4.5 Tests Results of the Quality of the Concrete Surface

The test results of each test on the quality of the concrete surface are shown in the test reports, appendices I-L. All tests except capillary water absorption were performed at 28 maturity days which was the time the samples were cut out of the specimens. The samples were marked with name on the test fields which again refers to the curing method.

Microstructure and Microcracks

All results of the microanalyses on the samples are given in appendix I. The results which concern the surface are given as follows. There are no remarks on concrete composition and concrete homogeneity. No coarse cracks are found in the sample from each field. The air content are unchanged in the surface. For fields marked 1-Horizontal, 1-Vertical and 2-Vertical the capillary porosity is unchanged. For fields marked 2- and 3-Horizontal the water-cement ratio is lower (approx 0.30-0.35) in the upper 3-5 mm. For field marked 3-Vertical the water-cement ratio is lower (approx 0.30-0.35) in a 0.5 mm thick zone approx 0.2-0.7 mm below the surface.

Figure 24 states the amount of cracks and depth of carbonation. The cracks are split up into cracks perpendicular to the surface (⊥) and cracks parallel to the surface (=). The length of the surface is approx 44 mm.

Figure 24. Microstructure and cracks.

Depth of carbonation (C) and number of cracks in the surface (outmost 2.5 mm)

Field marked	C mm	C along crack mm	Micro-crack ⊥ on surface	Micro-crack = on surface	Fine crack ⊥ on surface	Fine crack = on surface
1-Hor.	0.1	0.0	3	1	0	0
2-Hor.	0.0	0.0	0	0	0	0
3-Hor.	0.0	0.0	1	1	1	0
1-Ver.	0.0	0.0	4	0	0	0
2-Ver.	0.1	0.0	4	0	0	0
3-Ver.	0.0	0.0	0	2	0	0

Total amount of cracks in the whole thin section:	
Field marked 1-Horizontal:	Fine cracks: 0
	Micro cracks: 4
	Crack length : 0.3 mm to 2.0 mm
	Total crack length: 4.4 mm
Field marked 2-Horizontal:	none
Field marked 3-Horizontal:	Fine cracks: 2
	Micro cracks: 1
	Crack length : 0.2 mm to 1.6 mm
	Total crack length: 2.5 mm
Field marked 1-Vertical:	Fine cracks: 0
	Micro cracks: 4
	Crack length : 0.2 mm to 4.0 mm
	Total crack length: 5.7 mm
Field marked 2-Vertical:	Fine cracks: 0
	Micro cracks: 4
	Crack length : 0.3 mm to 2.1 mm
	Total crack length: 4.9 mm
Field marked 3-Vertical:	Fine cracks: 0
	Micro cracks: 2
	Crack length : 0.4 mm to 3.1 mm
	Total crack length: 3.5 mm

Chloride Penetration

The results of the chloride penetration are given in appendix J. Figure 25 states the chloride penetration.

Figure 25. Chloride penetration.

ASTM C 1202	
Field marked	Chloride penetration [Coulombs]
1-Horizontal	1475
2-Horizontal	2103
3-Horizontal	2671
1-Vertical	1421
2-Vertical	1904
3-Vertical	1352

Capillary Water Absorption

Test method TI-B 25 prescribes that samples are dried at 50 °C for minimum 2 days before testing. A drying period of about 1 week was chosen which results in very different degrees of saturation at the start of testing as shown in figure 26. The degree of saturation influence the speed of saturation.

The test reports are given in appendix K. They show that the tests were started at approx 39 maturity days.

Figure 26. Capillary water absorption

TI-B 25				
Field marked	Porosity [vol-%]	Degree of saturation start	Degree of saturation	Period of saturation [Hours]
1-Hor.	18.1	0.26	0.45	2.4
2-Hor.	14.6	0.24	0.50	2.5
3-Hor.	15.9	0.30	0.42	2.7
1-Ver.	20.5	0.28	0.41	2.4
2-Ver.	18.1	0.30	0.41	3.6
3-Ver.	18.4	0.30	0.37	2.0

Carbonation

The test report is given in appendix L. Figure 27 states the depth of surface carbonation as an 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 approx 21°C, 1 month is approx 1 maturity month.

Figure 30. Test results from test method NT Build 357.

Depth of Surface Carbonation in mm						
Field marked	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-Hor.	7	9	8	12	10	13
2-Hor.	9	10	13	14	14	15
3-Hor.	3	4	5	6	3	6
1-Ver.	0	0	0	0	0	0
2-Ver.	4	6	6	6	8	10
3-Ver.	3	4	0-3	3	0-3	4

5. Field Test Area

As described in chapter 2.3 half of the specimens cast in the laboratory were removed to the outdoor field test area at DTI, Taastrup, thus the specimens are exposed to Danish environmental conditions from an age of 28 maturity days. Furthermore three of the seven samples from each curing test in the field remained in plastic bags and at an age of 28 maturity days removed to the outdoor field test area at DTI, Taastrup. This procedure will make it possible later on to perform tests of the quality of the different curing methods.

The evaluation of all the obtained test results are a part of phase 4: Final Evaluation and Definition of Conformity Criterias where the test results from phase 1 and phase 3 will be evaluated together.

6. 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.

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