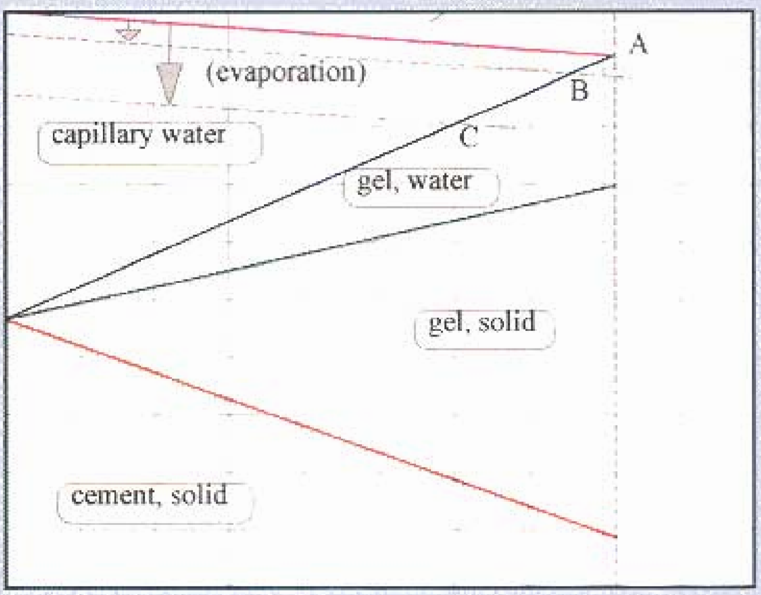
HETEK

Curing
Phase 4: Final Evaluation and Definition of Conformity Criteria



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Abstract

This report forms 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, the Phases 1 to 4, a Main Report and a Guideline. Phase 4: Final Evaluation and Definition of Conformity Criteria evaluates all the results of the tests performed in Phase 1 and Phase 3.

The tests performed in phase 3 include measurement of water loss from 4 specimens during 10 days as a function of time while they were subjected to different curing methods. In addition to this a plate of foundation for a bridge was subjected to 6 different types of curing. After 28 days samples were cut from the specimens and four types of tests were performed to investigate the effect of the curing. These four tests were: Crack formation, chloride penetration, capillary water absorption and carbonation depth (accelerated test).

The basic hypothesis is that the results of these tests are ralated to the formation of micro structure in the cement paste, which is influenced by the water loss.

The result of the evaluation was that only chloride penetration and carbonation depth could be correlated to the water loss and structure formation. The crack formation and the capillary water absorption showed very weak correlation to the water loss.

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0. Preface

This project which deals with 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 of at least 100 years in an aggressive environment.

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

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

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

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

This part of the project regarding curing is performed by:

Danish Technological Institute represented by the Concrete Centre:

- Marlene Haugaard (Head of the project)
- Kirsten Riis
- Tommy Nielsen
- Jette Schaumann

and

Danish Concrete Institute represented by the three contractors:

Højgaard & Schultz A/S - Per Fogh Jensen
Monberg & Thorsen A/S - Jan Graabek
Rasmussen & Schiøtz - Per Jeppesen

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

A 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.

April 1997
Per Fogh Jensen
Marlene Haugaard
Steering Committee of HETEK-Curing project

1. Introduction

The tests evaluated in this report are reported in detail in the phase 3 report: Verification Tests.

This report contains an evaluation of 4 curing tests performed in the laboratory and 6 curing tests performed in the field on the foundation for a bridge.

The figures in this report include the results from the Phase 2 report, Evaluation of Test Results, in order to make it possible to evaluate all the results together.

The results from the field tests are treated separately, as the water loss from these tests are not measured.

2. Test Methods and Results

The test methods and the results from the tests are described in detail in the reports from phase 1 and phase 3.

In phase 1, Laboratory Tests, 14 specimens were subjected to different curing methods in the laboratory, and 5 types of measurements were performed on each specimen: Evaporation test, micro crack formation, chloride penetration, capillary water absorption and carbonation. The results of these measurements are evaluated in phase 2, Evaluation of Test Results.

In phase 3, Verification Tests, 4 specimens (nos. 15 - 18) were subjected to different curing methods in the laboratory and a foundation in the field was subjected to 6 different curing methods (nos. F1-H, F2-H, F3-H, F1-V, F2-V and F3-V). In the laboratory tests the same types of measurements were performed on each specimen as in phase 1: Evaporation test, micro crack formation, chloride penetration, capillary water absorption and carbonation. In the field it was not possible to measure the evaporation, so only the last four types of measurements were performed. The results of these measurements are evaluated in this report together with the evaluation from phase 2.

The test programme performed in DTI's laboratory in phase 3 is described in figure 2.0.1.

Figure 2.0.1. Phase 3 test programme in laboratory.

	Surface			
Spec. 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 specimens 15-18 were cured during a period of 10 Mdays as described above.

Tests nos. 15 and 16 were performed with concrete recipe no. 6021 from 4K. The recipe was the same as that used in phase 3. The climatic conditions were 3.6 m/s, 20 °C and 50 % RH.

Tests nos. 17 and 18 were performed with concrete recipe No. A35LSFAA25L3 from Unicon. The recipe was the same as that used in the field test. The climatic conditions were 3.6 m/s, 20 °C and 70 % RH.

After the curing and evaporation tests the specimens were placed in a climate chamber at 20 °C and 65 % RH until 28 Mdays.

In the field six curing methods were performed on the foundation for a bridge construction cast with concrete recipe A35LSFAA25L3 from Unicon. The concrete recipe from Unicon was chosen by the contractors but was similar to the concrete recipe from 4K.

The six curing methods are described below (Horizontal indicates the upper surface of the foundation plate and Vertical indicates the vertical side of the foundation).

Test 1 - Horizontal:	Transparent plastic on the concrete at 1 Mh.
Test 2 - Horizontal:	Curing compound on the fresh, wet concrete surface, at 1 Mh.
Test 3 - Horizontal:	Curing compound on the concrete surface at 7 Mh.
Test 1 - Vertical:	Form liner on the concrete surface in the first 3 Mdays and curing compound on the concrete surface after demoulding.
Test 2 - Vertical:	Plywood formwork on the concrete surface in the first 3 Mdays and curing compound on the concrete surface after demoulding.
Test 3 - Vertical:	Timber formwork on the concrete surface in the first 3 Mdays and curing compound on the concrete surface after demoulding.

The climatic conditions in the field test period was measured by a mini-weather station. Further, the temperature in the concrete was measured by thermocouples in order to calculate the maturity development of the concrete.

At approximately 12 Mdays 7 samples with a diameter of 100 mm were taken from each curing field. The samples were put into plastic bags and transported to the laboratory where they were stored at approx 20 °C until 28 Mdays.

Four of the samples were used for measurements of micro crack formation, chloride penetration, capillary water absorption and carbonation. The other three were placed in the field test area together with specimens from phase 1.

The measurements were done as follows:

Micro Cracks TI-B 5 (87)
Three fluorescence impregnated thin sections, 30 x 45 mm, of each specimen have been analysed in microscope for crack number, crack width, crack length and crack orientation. The variation of the porosity was evaluated by studying the variation in water-cement ratio.

Chloride Penetration AASTHO T 277-83
Two cylinders of each specimen with diameter 100 mm and length 50 mm have been subjected to 60 V(dc) for 6 hours and the electric charge (expressed in Coulombs) passing through the specimen has been recorded.

Capillary Water Absorption TI-B 25
Three samples, 90 x 130 mm, thickness 30 mm, of each specimen have been tested for absorption of water versus time.

Carbonation NT BUILD 357
One sample, 100 x 100 x 300 mm, of each specimen has been exposed to a concentration of CO_2 at 3.0 % and the carbonation depth was measured 1, 2 and 3 months after start of exposure.

3. Theory and Evaluation

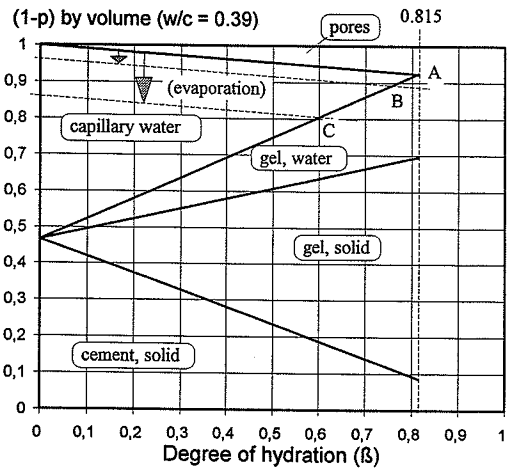
3.0 Formation of solid structure

In the phase 2 report Evaluation of Test Results the following equation has been found for calculation of $V_{cap=0}$ as a function of the initial W/C_e and the water loss dU during hydration:

$$V_{cap=0} = 0.857 + 0.143 / (1 + 2.29 * W/C_e) - 0.0354 * dU$$

V is the density of the cement paste by volume. Index cap = 0 indicates the density which can be obtained when the capillary water content becomes zero. The coefficients in the formula are only valid for the concrete used in this project at a thickness of 100 mm.

Figure 3.0.1: Porosity of cement paste during hydration as a function of the degree of hydration.



In *Figure 3.0.1* lines are drawn, that correspond to $W/C_e = 0.39$ (W/C_e of the specimens in the project range from 0.37 to 0.42 but as 0.39 is the most frequent value, it is used in this figure). It is obvious that the capillary water content becomes zero when the theoretical degree of hydration ß (equivalent to the degree of hydration of the cement) obtains the value 0.815. The maximum degree of hydration $ß_{max}$ based on measurements of development of strength and heat has the value $ß_{max}=1$ when the point A is reached. So the following relation exist:

$ß_{max} = ß / 0.815$ (valid for $W/C_e = 0.39$)

If evaporation takes place before point A has been reached, there will not be water enough left for the concrete to reach point A. In *Figure 3.0.1* two dotted lines are shown representing two levels of reductions in the capillary water content caused by evaporation from the concrete. It is obvious that the concrete can only reach the points B or C depending on the amount of evaporation. The lowest one of the two dotted lines represent the level of evaporation that has been measured from specimens 4 and 7.

Below (section 3.1) the values of $V_{cap=0}$ are calculated for each of the eighteen specimens and used as a parameter that represents the porosity of the structure formed in the concrete.

The basic hypothesis is that parameters like crack formation, chloride penetration rate, capillary suction and carbonation depth depend on $V_{cap=0}$.

This hypothesis forms the theoretical background for the requirements for the maximum evaporation of water before protecting against drying out and for the requirements as to when this protection can be removed, as described in "Almindelig arbejdsbeskrivelse" (AAB) [Vejregeludvalget, 1994] and "Basisbetonbeskrivelse" (BBB) [ATV-udvalget vedr. betonbygværkers holdbarhed, 1987].

In the following sections (3.2 - 3.5) this hypothesis is investigated.

3.1 Weight loss and hydration

In *Figure 3.1.1* the measured values of total weight loss at 10 Mdays are tabulated in descending order of $V_{cap=0}$. The negative value of specimen no. 10 represent a rise in weight during water curing.

Figure 3.1.1. Total measured weight loss (dU) and calculated structure density parameter ($V_{cap=0}$) by specimen no. sorted in desending order of $V_{cap=0}$. Field tests are not included in this figure, as weight losses from these tests are not measured.

Spec.- No.	dU (kg/m²)	$V_{cap=0}$ (m³/m³)	$ß_{max}$	Curing method
10	-0.67	0.948	1.05	Water cured
3	0.04	0.923	1.00	Mould in 10 Mdays
12	0.08	0.921	0.99	Mould in 3 Mdays + Foam-matt
18	0.05	0.920	1.00	Plastic after 2 Mh
2	0.22	0.918	0.98	Mould in 3 Mdays + Curing compound
8	0.23	0.917	0.98	Mould in 3 Mdays + Curing comp. - 44% RF
15	0.25	0.916	0.98	Mould in 3 Mdays + Curing compound
11	0.27	0.914	0.98	Mould in 1 Mday + Foam-matt
6	0.32	0.914	0.98	Mould in 1 Mday + Curing compound
14	0.34	0.912	0.97	Curing compound after 2 Mh
17	0.30	0.911	0.98	Mould in 3 Mdays + Curing compound
1	0.51	0.908	0.96	Mould in 3 Mdays
16	0.62	0.903	0.95	Curing compound after 2 Mh
13	0.66	0.901	0.95	Foam-matt after 5 Mh
5	0.91	0.893	0.93	Mould in 1 Mday
9	1.14	0.884	0.91	Curing compound after 5 Mh
4	3.39	0.804	0.74	Free surface
7	3.56	0.799	0.72	Free surface - 44% RF

As mentioned above it was not possible to measure the weight loss in the field tests and accordingly the field tests are not mentioned in *Figure 3.1.1.*

From the measured weather data and the concrete temperature a theoretical value of evaporation rate from the concrete can be calculated:

Measured values (average) on the day of casting:

- Concrete temperature 18 °C
- Air temperature 12 °C
- Air relative humidity 80 %
- Wind velocity 1 - 2 m/s

The vapour pressure difference between the concrete and the air is 1.0 kPa and the corresponding values of evaporation rates are:

- at 1 m/s wind speed: 0.2 kg/m²h
- at 2 m/s wind speed: 0.3 kg/m²h

Thus the evaporation rates from the fresh concrete can be evaluated to be around 0.25 kg/m²h according to the HETEK Guidelines.

The following relative degrees of hydration for the two concretes can be calculated from the heat development measurements:

Concrete	1 Mday	3 Mdays	10 Mdays
4-K	54.1 %	80.7 %	93.5 %
Unicon	52.2 %	80.5 %	93.7 %

3.2 Cracks

In the test method used in this project thin sections of the concrete have been produced by cutting, impregnating and grinding the concrete so that a thin slice of the concrete is left fastened on a glass plate. This thin section is studied under microscope.

In the test method is distinguished between three categories of surface cracks:

Micro cracks (width < 0.01 mm), fine cracks (0.01 mm < width < 0.1 mm) and *coarse cracks (0.1 mm < width)*

and between two categories of crack angles:

Cracks perpendicular to surface and *parallel to surface*:

Furthermore, the test method distinguishes between two categories of cracks:

Paste cracks and *adhesion cracks and defects*

The test reports present countings of 8 combinations of categories of cracks:

Surface (outmost 2.5 mm, area analysed ~ 100 mm²):

1. Micro cracks, perpendicular to surface
2. Micro cracks, parallel to surface
3. Fine cracks, perpendicular to surface
4. Fine cracks, parallel to surface
5. Coarse cracks, perpendicular to surface
6. Coarse cracks, parallel to surface

Internal structure (area analysed ~ 60 mm²):

7. Paste cracks
8. Adhesion cracks and defects

Furthermore, the length of each crack in the surface was recorded.

An important result was that no coarse cracks (type 5 and 6) were found in any of the 14 specimens.

Each of the parameters 1-8 has been investigated for correlation between the crack parameter and the structure density parameter $V_{cap=0}$ but no or only weak correlations could be found. As indicated in the arguments above, possible effects of cracks on transport phenomena depend on the volume or the length of the cracks, and therefore and in order to include as much information as possible from the measurements to rank the concretes, the following has been done for each specimen:

- The total length of all cracks (parallel and perpendicular) in the surface layer has been summed together for each specimen.
- The total number of cracks in the internal structure was calculated for each specimen.

The results are tabulated in *Figure 3.2.1.*

Figure 3.2.1. Total length of cracks in surface (outermost 2.5 mm) and number of paste etc. cracks, ranked by the length of surface cracks

Sp. no.	Surf. (mm)	Paste (no/mm²)	Rank	Curing method
7	0.0	0.05	1	Free surface - 44% RF
2-Hor	0.0	0.66	2	Cur. comp. after 1 Mh, plastic 20-88 Mh
5	3.6	0.19	3	Mould in 1 Mday
8	4.1	0.27	4	Mould in 3 Mdays + Cur.comp. - 44% RF
3-Hor	7.5	0.63	5	Cur. comp. after 7 Mh, plastic 20-88 Mh
4	8.7	0.16	6	Free surface
3-Ver	12.0	0.66	7	Timber formwork in 3 Mdays, cur.comp., pl.98-113 Mh
1-Hor	13.2	0.87	8	Plastic after 1 Mh
14	13.9	0.11	9	Curing compound after 2 Mh
2-Ver	14.7	1.08	10	Mould in 3 Mdays, cur.comp., pl.98-113 Mh
11	15.6	0.13	11	Mould in 1 Mday + Foam-matt
1-Ver	17.1	0.42	12	Mould and formliner in 3 Mdays, plastic 98-113 Mh
16	18.3	0.28	13	Curing compound after 2 Mh
2	22.2	0.82	14	Mould in 3 Mdays + Curing compound
6	23.0	0.46	15	Mould in 1 Mday + Curing compound
15	25.7	0.41	16	Mould in 3 Mdays + Curing compound
12	26.4	0.26	17	Mould in 3 Mdays + Foam-matt
17	29.7	0.42	18	Mould in 3 Mdays + Curing compound
13	30.4	0.53	19	Foam-matt after 5 Mh
18	36.6	0.57	20	Plastic after 2 Mh
1	37.0	0.86	21	Mould in 3 Mdays
9	46.6	0.16	22	Curing compound after 5 Mh
3	49.3	0.36	23	Mould in 10 Mdays
10	53.0	0.89	24	Water cured

To see if there is any correlation between the structure parameter $V_{cap=0}$ and the cracks measured in this section two graphs have been made, *figure 3.2.2 and 3.2.3*, where the two crack parameters listed in *figure 3.2.1* are drawn versus the structure parameter.

Figure 3.2.2. Total length of surface cracks in three samples (area analysed: 3 x 100 mm²) versus structure density parameter $V_{cap=0}$. (Empty markers: measurements made in phase 1. Filled markers: measurements made in phase 3).

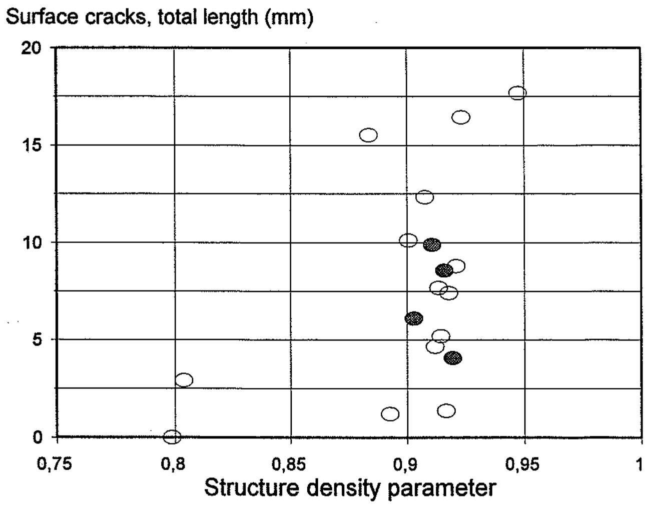
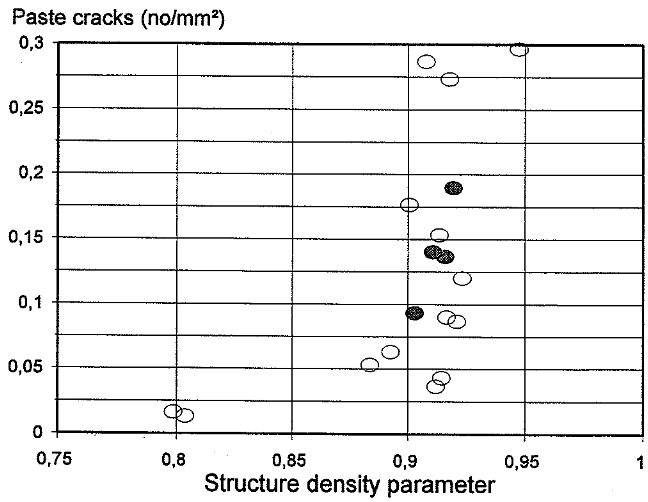


Figure 3.2.3. Average number of paste cracks in internal structure (area analysed: 60 mm²) versus structure density parameter $V_{cap=0}$. (Empty markers: measurements made in phase 1. Filled markers: measurements made in phase 3).



The two figures 3.2.2 and 3.2.3 show, as expected, that the concrete has a general tendency to form more cracks the more dense it is, although the correlation between cracks formation and structure density is very weak.

3.3 Chloride penetration

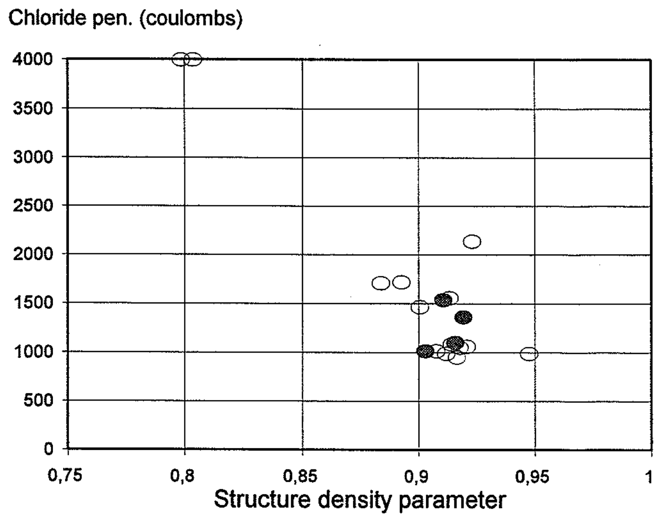
The results of the measurements are tabulated in *figure 3.3.1*. The results have been ranked in ascending order of chloride penetration rate.

Figure 3.3.1. Specimen no. versus values of chloride penetration (Coulombs), sorted in ascending order of chloride penetration.

Speci-men	Chl. pen. (Coulombs)	Rank	Curing method
8	951	1	Mould in 3 Mdays + Curing comp. - 44% RF
10	985	2	Water cured
14	985	3	Curing compound after 2 Mh
1	1013	4	Mould in 3 Mdays
16	1015	5	Curing compound after 2 Mh
2	1049	6	Mould in 3 Mdays + Curing compound
12	1059	7	Mould in 3 Mdays + Foam-matt
11	1084	8	Mould in 1 Mday + Foam-matt
15	1098	9	Mould in 3 Mdays + Curing compound
3-Ver	1352	10	Timber formwork in 3 Mdays, cur.comp., pl.98-113 Mh
18	1360	11	Plastic after 2 Mh
1-Ver	1421	12	Mould and form liner in 3 Mdays, plastic 98-113 Mh
13	1463	13	Foam-matt after 5 Mh
1-Hor	1475	14	Plastic after 1 Mh
17	1534	15	Mould in 3 Mdays + Curing compound
6	1556	16	Mould in 1 Mday + Curing compound
9	1710	17	Curing compound after 5 Mh
5	1717	18	Mould in 1 Mday
2-Ver	1904	19	Mould in 3 Mdays, cur.comp., pl.98-113 Mh
2-Hor	2103	20	Cur. comp. after 1 Mh, plastic 20-88 Mh
3	2139	21	Mould in 10 Mdays
3-Hor	2671	22	Cur. comp. after 7 Mh, plastic 20-88 Mh
4	>4000	23	Free surface
7	>4000	24	Free surface - 44% RF

The measured values of chloride ion penetrations have been plotted versus the structure parameter (see section 3.1) in *figure 3.3.2*. Specimens nos 4 and 7 have been plotted with the value 4000 coulombs, although the measurements only state that the values are higher than 4000 coulombs.

Figure 3.3.2. Chloride penetration versus structure density parameter $V_{cap=0}$. The points plotted with the value 4000 should really be >4000. (Empty markers: measurements made in phase 1. Filled markers: measurements made in phase 3).



The figure shows a correlation between structure density and chloride penetration (coulombs). This is in good agreement with what is expected, i.e., a less dense structure should allow more chloride ions to pass through.

3.4 Capillary Water Absorption

The samples were dried for a week in an oven at 50 °C and then placed on a water surface for more than 10 days with the test surface facing down. The samples were weighed before and regularly during the exposure to water. Afterwards the samples were dried in an oven at 105 °C until a constant weight was reached. Then the samples were filled with water using vacuum and then weighed under water to calculate their volume.

The degree of filling was calculated and plotted versus the square root of time.

The test method prescribes to find the point where the graph changes from a sloping line into a (almost) horizontal line by intersecting two tangents (placed at the start and at the end of the measurement period).

The results of this method are difficult to interpret, because in many measurements the curves do not change abruptly from a sloping line into a horizontal line. Instead of two straight lines the measurements often yield graphs that changes smoothly from an initial slope to almost horizontal.

The graphs have been interpreted in the prescribed manner to give values of Q_{cap} and t_{cap} which are the coordinates of the points of intersection mentioned above.

Investigations showed very low correlations between each of these two parameters and the structure density parameter $V_{cap=0}$.

In order to evaluate a combination of these two qualities, the following expression has been used (the factor 0.1 is used to give the two parameters Q_{cap} and t_{cap} the same weight).

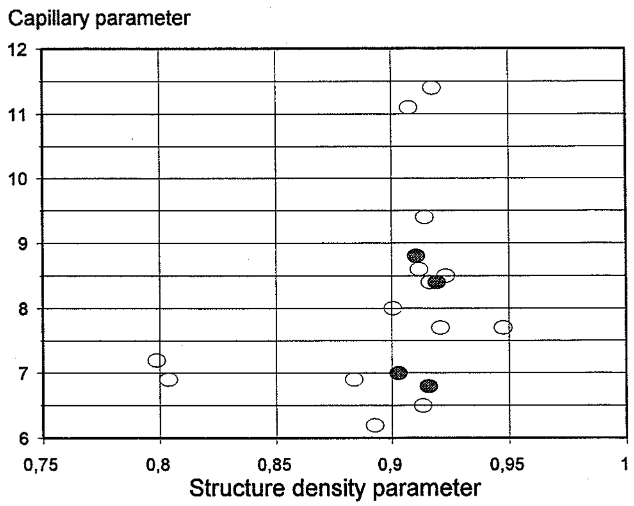
$$Cap = 0.1 \cdot Q_{cap} + t_{cap}$$

In *figure 3.4.1* the values of Cap are tabulated versus specimen number and sorted in order of descending values of Cap.

Figure 3.4.1. Specimen no. versus values of Q_{cap} and t_{cap} sorted in descending order of Cap

Spec. No.	Q_{cap} (%)	t_{cap} ($h^{0.5}$)	Cap	Rank	Curing method
2	61	5.3	11.4	1	Mould in 3 Mdays + Curing compound
1	61	5.0	11.1	2	Mould in 3 Mdays
11	60	3.4	9.4	3	Mould in 1 Mday + Foam-matt
17	58	3.0	8.8	4	Mould in 3 Mdays + Curing compound
14	42	4.4	8.6	5	Curing compound after 2 Mh
3	52	3.3	8.5	6	Mould in 10 Mdays
8	43	4.1	8.4	7	Mould in 3 Mdays + Curing comp. - 44% RF
18	71	1.3	8.4	8	Plastic after 2 Mh
13	49	3.1	8.0	9	Foam-matt after 5 Mh
12	56	2.1	7.7	10	Mould in 3 Mdays + Foam-matt
10	51	2.6	7.7	11	Water cured
7	38	3.4	7.2	12	Free surface - 44% RF
16	52	1.8	7.0	13	Curing compound after 2 Mh
4	46	2.3	6.9	14	Free surface
9	41	2.8	6.9	15	Curing compound after 5 Mh
15	51	1.7	6.8	16	Mould in 3 Mdays + Curing compound
2-Hor	50	1.6	6.6	17	Cur. comp. after 1 Mh, plastic 20-88 Mh
6	41	2.4	6.5	18	Mould in 1 Mday + Curing compound
5	40	2.2	6.2	19	Mould in 1 Mday
1-Hor	45	1.5	6.0	20	Plastic after 1 Mh
2-Ver	41	1.9	6.0	21	Mould in 3 Mdays, cur.comp., pl.98-113 Mh
3-Hor	42	1.6	5.8	22	Cur. comp. after 7 Mh, plastic 20-88 Mh
1-Ver	41	1.5	5.6	23	Mould and form liner in 3 Mdays, plastic 98-113 Mh
3-Ver	37	1.4	5.1	24	Timber form work in 3 Mdays, cur.comp., pl.98-113 Mh

Figure 3.4.2. Capillary parameter Cap = 0.1 · Q_{cap} + t_{cap} versus structure density parameter $V_{cap=0}$. (Empty markers: measurements made in phase 1. Filled markers: measurements made in phase 3).



In the *figure 3.4.2* the parameter Cap has been graphed versus the structure parameter $V_{cap=0}$. The figure shows, that no correlation exist between $V_{cap=0}$ and Cap. Therefore the conclusion must be that no correlation has been found between the structure density parameter $V_{cap=0}$ and the capillary suction process.

3.5 Carbonation depth

In order to rank the test results in this project the following steps have been used:

1. All the measured penetration depths have been extrapolated one by one to 100 years using the log-log model with slope 0.4 mentioned in the phase 2 report. Test results with no measured penetration depth were disregarded.
2. For each specimen the averages of the d_k and the d_{max} values were calculated.
3. The specimens were ranked according to d_k.

The result was as follows:

Figure 3.5.1. Specimens listed after equivalent carbonation depth (d_k) (equivalent to average carbonation depth after 100 years, assuming natural CO_2 content)

Speci-men no.	Eq. carb.depth (mm) d_k	d_{max}	Rank	Curing method
1-Ver	(0)	(0)	1	Mould and form liner in 3 Mdays, plastic 98-113 Mh
14	(0)	4.1	2	Curing compound after 2 Mh
8	(0)	5.2	3	Mould in 3 Mdays + Curing comp. - 44% RF
15	(0)	(7.5)	4	Mould in 3 Mdays + Curing compound
16	(0)	7.2	5	Curing compound after 2 Mh
3-Ver	4.0	8.0	6	Timber form work in 3 Mdays, cur.comp., pl.98-113 Mh
2	5.7	7.4	7	Mould in 3 Mdays + Curing compound
1	5.7	8.4	8	Mould in 3 Mdays
13	6.5	9.6	9	Foam-matt after 5 Mh
3-Hor	7.9	11.2	10	Cur. comp. after 7 Mh, plastic 20-88 Mh
12	8.3	14.7	11	Mould in 3 Mdays + Foam-matt
10	9.0	16.1	12	Water cured
17	10.2	19.0	13	Mould in 3 Mdays + Curing compound
9	11.0	15.3	14	Curing compound after 5 Mh
6	12.3	15.2	15	Mould in 1 Mday + Curing compound
2-Ver	12.3	15.3	16	Mould in 3 Mdays, cur.comp. 3 Mdays, pl.98-113 Mh
11	13.9	19.6	17	Mould in 1 Mday + Foam-matt
3	17.4	21.9	18	Mould in 10 Mdays
1-Hor	17.6	23.8	19	Plastic after 1 Mh
5	18.8	22.3	20	Mould in 1 Mday
2-Hor	25.1	27.3	21	Cur. comp. after 1 Mh, plastic 20-88 Mh
18	33.9	42.2	22	Plastic after 2 Mh
7	39.7	46.9	23	Free surface - 44% RF
4	42.6	47.9	24	Free surface

The equivalent carbonation depth has been plotted versus the structure density parameter $V_{cap=0}$ in *figure 3.5.2.*

Figure 3.5.2. Values of carbonation depths, forecasted until 100 years, versus structure density parameter $V_{cap=0}$. The forecast is based on a concentration factor=100 on the time scale and a log-log time dependence with a slope of 0.4 (decades/decade). (Empty markers: measurements made in phase 1. Filled markers: measurements made in phase 3).

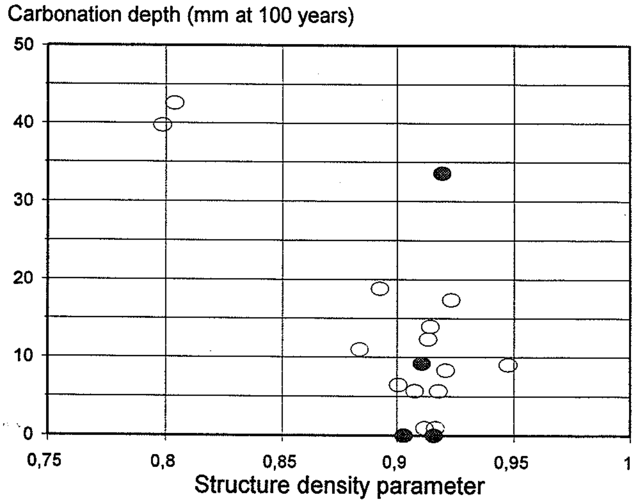


Figure 3.5.2 shows a general correlation between the structure density parameter $V_{cap=0}$ and carbonation depth. This is in good agreement with what may be assumed, i.e., that a less dense structure allows more carbonation than a more dense structure.

3.6 Evaluation

The total quality of the surface of the specimens has been rated in the following manner: The range of values of $V_{cap=0}$ and each of the four measured parameters (crack formation, chloride penetration, capillary suction and carbonation) have been normalised into the range 0 to 100. (The crack formation parameter is calculated as the average value of the parameters calculated from the surface cracks and the paste cracks).

With the normalised values a linear regression analysis has been performed on each of the four parameters as a function of the structure density parameter $V_{cap=0}$. The results are shown below:

Figure 3.6.1 Results of regression analysis

Test	Correlation coefficient	Slope
3.2 (cracks)	0.37	0.56
3.3 (chloride pen.)	0.84	-1.10
3.4 (cap. suct.)	0.10	0.29
3.5 (carbonation)	0.52	-0.87

The four normalised parameters have been weighted with the slope and added together to form a weighted sum parameter called WSP.

As an example the WSP for test No. 1 is calculated as follows:

$$WSP_1 = 0.56 \cdot 75 - 1.10 \cdot 2 + 0.29 \cdot 95 - 0.87 \cdot 13 = 56$$

Figure 3.6.2. Summary of measurements, normalised parameters (range 0 - 100) (WSP = weighted sum of parameters)

Test no.	$V_{cap=0}$	Cracks	Chloride pen.	Capillary abs.	Carbonation	WSP
1	73	75	2	95	13	56
2	80	59	3	100	13	47
3	84	63	39	54	41	-27
4	4	10	100	29	100	-183
5	63	12	25	17	44	-54
6	77	43	20	22	29	-17
7	1	2	100	33	93	-180
8	79	16	0	52	2	22
9	57	51	25	29	26	-13
10	100	91	1	41	21	43
11	78	21	4	68	33	-2
12	82	37	4	41	20	12
13	68	53	17	46	15	11
14	76	18	1	56	2	23
15	79	43	5	27	0	27
16	70	30	2	30	0	23
17	75	47	19	59	22	4
18	81	38	13	52	79	-47
1, Horizontal		53	17	14	41	-21
2, Horizontal		31	38	24	59	-69
3, Horizontal		36	56	11	19	-55
1, Vertical		36	15	8	0	5
2, Vertical		64	31	14	29	-20
3, Vertical		42	13	0	9	1

Figure 3.6.3. Specimen no. and curing methods ranked in ascending order of WSP. $ß_{max}$ represent the degree of hydration which is obtainable at the actual water loss ($ß_{max}$=1 with no water loss).

Spec. No.	WSP*	$ß_{max}$	Curing method
1	56	0.96	Mould in 3 Mdays
2	47	0.98	Mould in 3 Mdays + Curing compound
10	43	1.05	Water cured
15	27	0.98	Mould in 3 Mdays + Curing compound
14	23	0.97	Curing compound after 2 Mh
16	23	0.95	Curing compound after 2 Mh
8	22	0.98	Mould in 3 Mdays + Curing comp. - 44% RF
12	12	0.99	Mould in 3 Mdays + Foam-matt
13	11	0.95	Foam-matt after 5 Mh
1-Ver	5	-	Mould and form liner in 3 Mdays, plastic 98-113 Mh
17	4	0.98	Mould in 3 Mdays + Curing compound
3-Ver	1	-	Timber form work in 3 Mdays, cur.comp., pl.98-113 Mh
11	-2	0.98	Mould in 1 Mday + Foam-matt
9	-13	0.91	Curing compound after 5 Mh
6	-17	0.98	Mould in 1 Mday + Curing compound
2-Ver	-20	-	Mould in 3 Mdays, cur.comp., pl.98-113 Mh
1-Hor	-21	-	Plastic after 1 Mh
3	-27	1.00	Mould in 10 Mdays
18	-47	1.00	Plastic after 2 Mh
5	-54	0.93	Mould in 1 Mday
3-Hor	-55	-	Cur. comp. after 7 Mh, plastic 20-88 Mh
2-Hor	-69	-	Cur. comp. after 1 Mh, plastic 20-88 Mh
7	-180	0.72	Free surface - 44% RF
4	-183	0.74	Free surface

Notes: WSP*:Weighted sum of normalised, measured parameters.

4. Conclusion

The basic hypothesis, as described in chapter 3, is that parameters like crack formation, chloride penetration rate, capillary suction and carbonation depth depend on the structural density of the cement paste.

A theoretically calculated parameter (structure density parameter $V_{cap=0}$) has been used to describe the final cement paste density by volume that can be obtained as a function of the equivalent w/c ratio and the amount of water evaporated until 10 maturity days after casting.

Four parameters have been measured to evaluate the effect of the various curing methods. Each of these parameters has been correlated to the structure density parameter $V_{cap=0}$. From the results the following conclusions can be drawn:

- No correlation has been found between the structure density parameter $V_{cap=0}$ and parameters used to describe capillary suction.
- Weak correlation has been found between structure density parameter $V_{cap=0}$ and the formation of cracks in the surface (2.5 mm) and in the cement paste.
- Weak correlation has been found between structure density parameter $V_{cap=0}$ and carbonation depth.
- Correlation has been found between structure density parameter $V_{cap=0}$ and chloride penetration.

A weighted sum of the four parameters has been calculated and used to rank the curing tests in the following manner: Each of the parameters has been recalculated to give values in the range from 0 to 100. These normalised values have been multiplied by the slope of the regression line between the parameters and the structure density parameter. Finally the products have been added together. The weighted sum of parameters has been used to rank the results.

Based on this ranking two of the curing methods separate from the others as they are ranked with very low values of the weighted sum of parameter. These two tests are the tests performed with a free surface.

The rest of the curing methods yield higher values of the weighted sum of parameters. Even though the ranking is based on minor changes in the weighted sum of parameters these curing methods can be divided into two groups:

1. The 12 curing methods with the highest values of the weighted sum of parameters:
   - Mould in 3 Mdays, with or without curing
   - Water curing
   - Curing compound on fresh concrete and
   - Foam-matt placed at the time of setting (5 Mh).

2. The 10 curing methods with average values of the weighted sum of parameters:
   - Curing compound at the time of setting (5 Mh)
   - Mould in 1 Mday, with or without curing afterwards
   - Mould in 10 Mdays
   - Plastic on the fresh concrete

Only two of the full-scale tests (2-Vertical and 2-Horizontal) do not confirm this pattern, as their values of the weighted sum of parameters are average.

Some of the tests have been performed more than one time. The four laboratory tests Nos. 2, 15, 8 (where the RH was changed) and 17 (where another type of concrete was used) were all with the curing method mould in 3 Mdays followed by curing. They have shown almost the same results. Laboratory tests Nos. 14 and 16, curing compound on fresh concrete, have shown exactly the same results. These results indicate a good reproducibility in the laboratory.

Laboratory test No. 18 and full scale test No. 1-Hor, both with plastic on the fresh concrete, have shown almost the same results. The wind velocity in the laboratory tests has been slightly higher (3.6 m/s) than in the field (1-2 m/s) and the temperature difference between the air and the concrete has been slightly higher in the field (6 °C) than in the laboratory (around 0 °C). The different test results may be explained by these temperature differences or by the common variation in the test results. Compared to the results from the tests where curing compound was used on fresh concrete, the tests with plastic have shown lower values. This indicates a lower efficiency of plastic than of curing compound, presumably caused by the fact that it is difficult to keep the plastic tight to the concrete surface, even in the laboratory tests.

Field tests Nos. 1-Ver (Mould with form liner in 3 Mdays followed by curing compound) and 3-Ver (Timber form work in 3 Mdays followed by curing compound) have shown the same results. This indicates that use of form liner, which is expensive, is not better than the old-fashioned practice of using timber form work, which is cheaper. Both field test No. 1-Ver and 3-Ver have shown slightly higher values than field test No. 2-Ver (mould in 3 Mdays followed by curing compound). The differences between the results are minor. It must of course be remembered that these comments are based on few results.

It is also remarkable that laboratory tests Nos. 14 and 16 (curing compound on fresh concrete) have shown high values and the comparable field test No. 2-Hor has shown a rather low value. However, no explanation can be found to this difference.

For all methods using mould for 1 or 3 Mdays no significant effect of additional use of form liner, curing compound or foam matt has been found.

The result of the project is that the hypothesis has been confirmed for class A concrete with fly ash and micro silica and with an equivalent water/cement ratio of 0.38.

Three remarkable achievements are:

1. Curing with curing compound on a fresh concrete has given good results except in one of the field tests.

2. Curing in mould for 10 Mdays has obtained a low rating as also seen in a previous test.

3. Only few values of crack formation have been obtained in specimens without curing (free surface).

If these results can be shown to be general, great improvements in the contractors procedures can be obtained, but further investigations are necessary to confirm the results.

The remarkable result with curing compound after 2 maturity hours must be investigated further in a test series with different curing compound types and concrete types. The results with curing in mould for 10 maturity days are not better than those with mould for 3-5 maturity days. This is a confirmation of a previous result, reported in [Lundberg, 1994], and must lead to a less restricted requirement on the total curing time, as already seen in project materials.

It must be emphasized, that the low values of crack formation in concretes without curing (with free surface), are in accordance with theoretical considerations saying that the micro cracks in concretes with low water/cement ratios (< 0.45) are a result of the hydration process. This means, that few cracks should be expected, when the hydration process is slowed down because of drying out of the concrete surface. If no micro cracks are found in the surface of a concrete with low w/c ratio, it may indicate that the concrete has not been cured properly.

The overall conclusion from the curing tests is that the concrete surface must be protected against evaporation to ensure a sufficiently dense cover of the concrete. The investigation also seems to confirm the ordinary requirements in AAB, where the requirement is that the duration of curing of concrete constructions in aggressive and extra aggressive environment must be so long that it has obtained more than 85-90 % degree of reaction based on the adiabatic heat development.

5. Conformity Criteria

In The Danish Road Directorate's specifications for concrete construction projects the "Almindelig arbejdsbeskrivelse" (AAB) [Vejregeludvalget, 1994] the requirements regarding curing are stated to ensure a good concrete quality especially of the concrete surface layer. The requirements are as follows:

"The contractor must protect the surfaces of the concrete against drying out. Unless otherwise proved to be sound, the protection shall be set up as soon as possible, before a quantity of 1.5 kg/m² of water has evaporated from the surface, however, not later than 1 hour after setting time.

These quantities of water corresponds to concrete layers equal to or thicker than 0.2 m. If the layer thickness is less than 0.2 m, the allowed quantity of evaporated water shall be reduced in proportion to the thickness. If the quantity of evaporated water is not documented by calculations based on the actual situation, the protection shall be started before one hour after casting.

The protection may, if necessary, be temporary prior to finishing.

Unless otherwise proved, the protection against drying out shall be retained until the relevant maturity, given in figure 12 (equivalent curing time at 20 °C), has been reached in the top layer of the concrete (measured in a depth of maximum 10 mm).

If the setting time exceeds 5 hours after mixing, the required maturity shall be increased correspondingly.

Figure 12. Earliest time for removal of protection against drying out

Environmental class	*Maturity hours*
C (Extra aggressive)	*180*
A (Aggressive)	*120*
M (Moderate)	*36*

"

The investigations in this project seem to confirm the overall requirements behind the fixed value of required minimum time in AAB, according to which the duration of curing of concrete constructions in aggressive and extra aggressive environment must continue until more than 85-90% degree of reaction has been obtained, based on measurement of the adiabatic heat development. This degree of reaction corresponds to a duration of the period of protection against drying out of approximately 90-120 maturity hours depending on the type of concrete. A requirement of 180 maturity hours in extra aggressive environmental class should be considered to be a conservative value, even when no knowledge on the heat development of the actual concrete exists.

In some specifications the requirements are as much as 240 maturity hours total curing time of concrete constructions. The results in this project indicate that the requirement of 120 maturity hours in aggressive environmental class should be maintained or reduced into 96 maturity hours, and the requirement in extra aggressive environmental class should be reduced into 120 maturity hours.

Only few of the investigations have been concentrated on early protection by using plastic, foam mats or curing compound on the fresh concrete, and so they can not lead to any changes in the well known conformity criteria right now. Such changes will require further investigations concentrated on the early protection of the concrete surface.

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List of Symbols

W Water content in concrete (kg/m^3)
C Cement content in concrete (kg/m^3)
FA Fly ash content in concrete (kg/m^3)
MS Micro silica content in concrete (kg/m^3)
W/C_e Effective water/cement ratio in concrete (kg/m^3)
($C_e = C + 0.5 * FA + 2 * MS$)

ß Degree of hydration (by volume of cement(

dU Water loss by evaporation from concrete (kg/m^2)
dW Water loss by evaporation from cement paste (m^3/m^3)

p_0 Porosity of cement paste at time of mixing (m^3/m^3)

$V_{cap=0}$ Volume ratio of (cement + gel) in cement paste, when capillary water content becomes zero

NB: In this project the maturity is defined as zero at the time of mixing.
The following abbreviations are used:
Mday = maturity days
Mh = maturity hours.

Appendices

Appendix A

Eq. W/C, air content and slump of the delivered concrete

Specimen no.	Equivalent water-cement ratio	Air content [%]	Slump [mm]
4K (recipe No. 6021)			
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
15	0.38	4.7	70
16	0.38	4.7	70
Unicon (recipe No. A35LSFAA25L3)			
17	0.42	4.4	55
18	0.42	4.4	55
Field tests	0.42	4.4	55

Appendix B

The climatic condition during the first 10 Mdays (evaporation test)

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
15	21	50	3.6
16	21	50	3.6
17	20	69	3.6
18	20	69	-

Appendix C

Weight losses during the first 10 Mdays (evaporation test)

Specimen no.	Plywood	Free surface	Curing compound	10 mm Foam-matt	Wet surface
	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	-	-
15	0.03	0.07	0.15	-	-
16	-	0.26	0.36	-	-
17	0.00	0.12	0.18	-	-
18	-	-	-	0.05 *	-

* Plastic

In the field tests no measurement of weight loss was performed.

Appendix D

Microanalysis (TI-B 5)

Specimen no.	C mm	C along crack mm	Micro-crack ⊥	Micro-crack =	Fine crack ⊥	Fine crack =
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	2.6	0.0	0.0	1.0
4	4.0	0.0	3.0	5.3	0.0	0.3
5	1.7	0.0	0.6	0.0	0.0	0.0
6	0.3	2.2	5.3	0.0	0.6	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	5.6	6.0	1.3	2.3
11	0.5	0.8	2.6	0.0	0.6	0.0
12	0.2	0.4	0.3	0.0	0.3	0.3
13	0.6	2.1	1.6	1.0	0.0	2.6
14	0.4	2.3	0.6	4.6	0.0	0.0
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
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

Appendix E

Chloride penetration (AASTHO T277-83)

Chloride penetration	
Specimen no.	Chloride penetration [Coulombs]
8	951
10	983
14	985
1	1013
2	1049
12	1059
11	1084
13	1463
6	1556
9	1711
5	1717
3	2239
4	>4000
7	>4000
15	1098
16	1015
17	1534
18	1360
1-Hor.	1475
2-Hor.	2103
3-Hor.	2671
1-Ver.	1421
2-Ver.	1904
3-Ver.	1352

Appendix F

Capillary water absorption (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
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
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

Appendix G

Carbonation depth (mm) (NT Build 357)

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
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
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