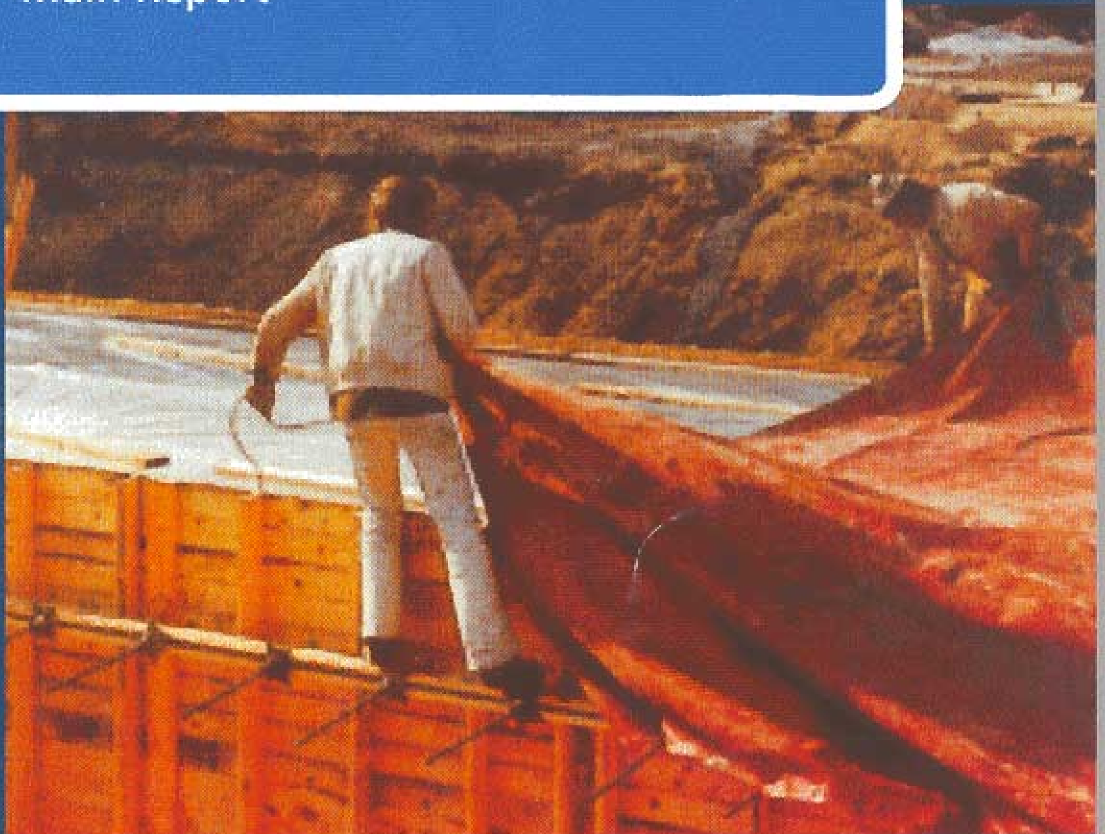
HETEK

Curing
Main Report



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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.

This report is a summary of the 24 curing tests performed in this part. The first 16 tests were performed in the laboratory with the same concrete recipe used for casting. This concrete recipe is a class A concrete with a water/cement-ratio of max. 0,40 which also is used in HETEK, part No. 3+4. The last 8 curing tests are partly 2 tests performed in the laboratory and partly 6 tests performed on a bridge construction which is the project's full-scale test. For casting of the last 8 curing tests is used a class A concrete with a water/cement-ratio of max. 0,45 chosen by the contractor on the bridge construction which was used for the full-scale test. The full-scale test was performed to verify the theory based on the first 14 curing methods. Hereby it was also possible to test form liner which had not been possible to test in a laboratory due to lack of form pressure.

The tests have been evaluated and two remarkable results have been found. Firstly, the tests show that you can not obtain a tighter concrete surface by curing the concrete surface up to 10 days of maturity compared to what can be achieved at 3 - 5 days of maturity. Secondly, the tests show that sealing sprayed on the concrete surface even 2 hours of maturity after the mixture of the concrete gives a tight concrete surface. This is surprising as producers of sealings do normally not recommend that sealing is sprayed on the concrete surface before the concrete has set.

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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 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 at least 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.

The 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
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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 Criteria
HETEK - Curing - Main Report
HETEK - Curing - Guideline.

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

1. Introduction

An important property of a concrete, which is to be used in aggressive or extra aggressive environment class, is that its water content is just sufficient to allow the hydration process to run to an end. A low water content provides a dense structure, because the cement paste does not contain a surplus of water, which might leave water filled pores in the concrete after hydration. However, if some of the water evaporates from the concrete during the hydration process, the hydration will stop before sufficient strength and stiffness of the concrete has been obtained. So it is important to cure the surface of the fresh concrete and protect it from evaporation in an efficient manner, so that it can reach a sufficient state of hydration.

The evaporation from the surface of the concrete is strongest, while the concrete is fresh, so it is important to start the curing as soon as possible in order to avoid crack formation caused by plastic shrinkage. Curing also ensures that the concrete maintains a sufficient amount of water to reach a proper degree of hydration in the surface. However, in many cases the concrete surface has to undergo further treatment very soon after it has been cast, e.g. in order to produce surface structure which is especially smooth. In such cases it may be necessary to perform a temporary curing of the concrete.

It is also important to maintain the curing for so long time, that the concrete surface has reached a state of hydration, sufficient to establish a good quality of the surface layer and make it resistant to penetration of chloride ions, carbon dioxide, sea water etc.

In the Danish standards for concrete structures demands on the curing of concrete can be found. They include demands on the time allowed to elapse before curing is established, and on the length of the curing period. During the last years there has been a tendency to increase these demands in the direction of a shorter initial period and a longer curing period.

Investigations performed by DTI and Dansk Beton Teknik A/S [Lundberg, 1994] have indicated, that keeping the concrete for a shorter period in the mould combined with adding curing compound after demoulding, results in a lower amount of micro cracks in the surface, compared to the situation, where the concrete is kept in the mould for a longer period.

As the demand on the curing is only one of many demands placed on the concrete production process, it is very important to study the effect of different curing methods to make it possible for the contractor to chose the curing method, which best adapts to each individual casting process.

2. Tests and Results

The report HETEK, Curing, State of the Art [Anette Berrig, Marlene Haugaard and Per Fogh Jensen, 1996] described the problems concerning curing of concrete and different curing methods were selected for testing. These methods included commonly used methods (keeping the concrete in the mould, covering it with diffusion tight materials, spraying it with curing compound, etc.) as well as some extreme variants (no curing at all, keeping the surface wet, keeping the concrete in the mould for a long time, etc.). In Phase 1 of the project a total of 14 curing tests were performed in DTI's laboratory under controlled climatic conditions. The results from these tests were reported in the Phase 1 report [Kirsten Riis and Marlene Haugaard, 1996].

For verification of the tests performed in Phase 1 a total of 10 tests were performed in Phase 3. 4 of these tests were performed in DTI's laboratory under conditions similar to those in Phase 1, and 6 tests were performed on site during construction of a bridge. The on site tests made it possible to test two curing methods, which were not well suited for the laboratory environment (form liner and timber formwork). The results from the 10 tests in Phase 3 were reported in the Phase 3 report [Kirsten Riis and Marlene Haugaard, 1997].

2.1 Tests

Curing tests nos. 1 to 18 were performed in DTI's laboratory, while the 6 tests with label 'Horizontal' or 'Vertical' were performed on site on a foundation for a bridge.

Figure 1: Duration of curing in maturity hours

Test No.	Mould	Free surface	Curing compound	Foam matt	Wet surface	Plastic
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	-	-	-
15**	1-81	81-83	83-240	-	-	-
16**	-	1-2	2-240	-	-	-
17	2-75	75-77	77-241	-	-	-
18	-	-	-	-	-	2-243
1- Horizontal	-	-	-	-	210-297	1-210
2- Horizontal	-	-	1-297	-	119-297	20-88
3- Horizontal	-	1-7	7-297	-	119-297	20-88
1- Vertical	1-79	79-284	-	-	79-284	98-113
2- Vertical	1-79	79-80	80-284	-	79-284	98-113
3- Vertical	1-79	79-80	80-284	-	79-284	98-113

The climate of the laboratory (test nos. 1-18) was:
Temperature 20°C, wind velocity 3.6-3.7 m/s and relative humidity 63-70 %.

The climate during the on site tests (labelled Horizontal and Vertical) was measured continuously close to the on site test area during the test period. Averages of the values were:
Temperature 7.6°C, wind velocity 1.2 m/s and relative humidity 87 %.

* Temperature 22 °C.
** Relative humidity 44-50 %.

A short description of the curing methods:

Mould: In the curing tests Nos. 1 to 18 and 3, Vertical the mould was waterproof plywood, 18 mm. In the test 3, Vertical the mould was timber formwork. In test 2, Vertical the plywood was covered with form liner. In all the tests the mould was treated with release agent (based on water and esther) except where the form liner was used.

Free surface: No curing was used on the surface.

Curing compound: Only one brand of curing compound was used in the curing tests. It was based on water and esther and its efficiency has been measured to be 84 % according to the test method TI-B 33. In the laboratory tests Nos. 2, 6, 8, 9 and 14-17 the amount 250 ml/m² of curing compound, as prescribed by the manufacturer, was sprayed onto the concrete surface. In the tests on site a bigger amount than prescribed was used.

Foam matt: A matt of 10 mm extruded polyethylene foam was placed on the surface.

Wet surface: In test no. 10 the concrete surface was covered with a hessian sack, which was kept wet by frequent watering. In the on site tests the label indicates periods, when the surfaces were subjected to rain.

Plastic: A transparent plastic foil was placed on the surface.

2.2 Concrete recipes

Only two types of concrete have been used in the tests. In the tests nos. 1 to 16 the concrete was based on recipe no. 6021 from 4K, see figure 2. This concrete was selected by the steering committee, and it is identical with that used in HETEK task 3 and 4. In the rest of the tests (laboratory tests nos. 17 and 18 and the 6 tests on site) the concrete was based on recipe no. A35LSFAA25L3 from Unicon. This recipe was selected by the contractor of the concrete bridge, where the on site tests were performed.

A common feature of the two recipes is, that they are well suited for use in great outdoor constructions such at bridges, roads, tunnels, etc.

Figure 2: Concrete recipe no. 6021 from 4K (equivalent w/c = 0.38)

Material	Description	kg/m^3
Cement	Low-alkali Sulfat resistant cement CEM I 42,5 (HS/EA/≤2)	285
Fly ash	Danaske	60
Silica fume	Elkem	12
Water	Water	127
Fine aggregate	RN-Avedøre, 0-4/A	758
Coarse aggregate	Rønne granit, 8-16/A	535
Coarse aggregate	Rønne granit, 16-25/A	565
Air entrainment	Conplast 316 AEA 1:1, Fosroc	0.357
Plasticiser	Conplast 212, Fosroc	1.428
Superplasticiser	Peramin F, Fosroc	2.856

Figure 3: Concrete recipe no. A35LSFAA25L3 from UNICON (equivalent w/c = 0.41)

Material	Description	kg/m^3
Cement	Low-alkali Sulfatresistant cement CEM I 42,5 (HS/EA/≤2)	274
Fly ash	Danaske	61
Silica fume	Powder	16
Water	Water	134
Fine aggregate	RN-Avedøre, 0-4/A	733
Coarse aggregate	Rønne granit, 4-16/A	679
Coarse aggregate	Rønne granit, 16-25/A	453
Air entrainment	Conplast 316 AEA 1:5, Fosroc	1.6
Plasticiser	Conplast 212, Fosroc	1.1
Superplasticiser	Peramin F, Fosroc	1.8

2.3 Results

The curing tests nos. 1 to 18 were carried out in two climate controlled wind tunnels in DTI's laboratory. The wind tunnels included scales for continuous recording of the weight changes of the test specimens caused by evaporation from the concrete surface being tested.

In figure 4 the total amount of water evaporated from each specimen is tabulated. In tests where curing compound has been used, the measured water losses from the specimens have been reduced by the water loss from the curing compound itself.

Figure 4: Water loss by evaporation from specimens until 10 maturity days

Curing test No.	Total water loss [kg/m^2]
1	0.51
2	0.22
3	0.04
4	3.39
5	0.91
6	0.32
7	3.56
8	0.23
9	1.14
10	-0.67
11	0.27
12	0.08
13	0.66
14	0.34
15	0.25
16	0.62
17	0.30
18	0.05

After the curing tests the specimens used in the laboratory tests nos. 1 to 18 were moved to a climate chamber with temperature 20 °C and relative humidity 65 %, where they were stored until 28 maturity days. The specimens from the on site tests stored in air tight plastic bags at a temperature of 20 °C until 28 maturity days.

After the samples for the tests had been prepared, the remaining parts of the specimens were moved to an outdoor location, where they were store in such a way, that they were subjected to normal Danish weather conditions with temperature changes, sunshine, rain, etc. The idea behind this is that it is possible to study the specimens at a later point in time.

Figure 5 shows the chloride penetration of the concrete surface tested at 28 maturity days according to ASTM C 1202.

Figure 5: Chloride penetration test at 28 maturity days (ASTM C 1202)

Test No.	Chloride permeability [Coulombs]
1	1013
2	1049
3	2139
4	>4000
5	1717
6	1556
7	>4000
8	951
9	1710
10	985
11	1084
12	1059
13	1463
14	985
15	1098
16	1015
17	1534
18	1360
1- Horizontal	1475
2- Horizontal	2103
3- Horizontal	2671
1- Vertical	1421
2- Vertical	1904
3- Vertical	1352

Figure 6 shows the carbonation depth of the concrete surface tested at 1 month, 2 months and 3 months after sampling, which happened at 28 maturity days according to NT Build 357.

Figure 6: Carbonation depth (NT Build 357)

Test No.	1 month		2 months		3 months	
	Average [mm]	Max. [mm]	Average [mm]	Max. [mm]	Average [mm]	Max. [mm]
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- Horizontal	7	9	8	12	10	13
2- Horizontal	9	10	13	14	14	15
3- Horizontal	3	4	5	6	3	6
1- Vertical	0	0	0	0	0	0
2- Vertical	4	6	6	6	8	10
3- Vertical	3	4	0-3	3	0-3	4

Thin sections made perpendicular to the concrete surface were investigated to determine the amount of cracks in the concrete surface. Figure 7 shows the total length of cracks in the utmost 2.5 mm of the surface and the number of paste cracks in the internal structure. The thin sections were tested according to TI-B 5.

Figure 7: Crack formation analysis made on thin sections perpendicular to the concrete surface (TI-B 5)

Test No.	Total length of cracks close to the surface (utmost 2.5 mm) [mm]	Internal paste cracks [No/mm^2]
1	12.3	0.29
2	7.4	0.27
3	16.4	0.12
4	2.9	0.05
5	1.2	0.06
6	7.7	0.15
7	0.0	0.02
8	1.4	0.09
9	15.5	0.05
10	17.7	0.30
11	5.2	0.04
12	8.8	0.09
13	10.1	0.18
14	4.6	0.04
15	8.6	0.14
16	6.2	0.09
17	9.9	0.14
18	12.2	0.19
1- Horizontal	4.4	0.29
2- Horizontal	0.0	0.22
3- Horizontal	0.9	0.31
1- Vertical	5.7	0.14
2- Vertical	4.9	0.36
3- Vertical	3.5	0.22

Figure 8 shows the capillary water absorption of the concrete surface. The tests were performed according to TI-B 25, which means that the samples were dried out at 50°C before testing.

Figure 8: Capillary water absorption (TI-B 25)

Test No.	Degree of saturation	Time of saturation [h]
1	0.61	5.6
2	0.63	8.1
3	0.53	4.0
4	0.48	5.3
5	0.41	3.5
6	0.42	3.2
7	0.40	7.3
8	0.44	17.6
9	0.41	6.6
10	0.54	2.3
11	0.61	3.6
12	0.56	3.4
13	0.50	4.0
14	0.43	15.2
15	0.51	2.8
16	0.52	3.2
17	0.58	9.3
18	0.71	1.6
1- Horizontal	0.45	2.4
2- Horizontal	0.50	2.5
3- Horizontal	0.42	2.7
1- Vertical	0.41	2.4
2- Vertical	0.41	3.6
3- Vertical	0.37	2.0

3. Evaluation of Results

The results of the measurements following the curing tests were evaluated in the Phase 2 and Phase 4 reports [Tommy Nielsen and Marlene Haugaard, 1997].

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

In order to investigate this hypothesis a structure density parameter called $V_{cap=0}$ was calculated for each specimen in the curing test. $V_{cap=0}$ represent the maximum volumetric density, that theoretically can be obtained in a cement paste, in which all the capillary water is either used for hydration or removed by evaporation. $V_{cap=0}$ is calculated from the data in the concrete recipe and the amount of water evaporated during curing. The calculation is based on the theory of Powers [Powers, 1948].

In a concrete with a low w/c ratio (<0.45) only a certain fraction β_0 of the cement can be hydrated, even if no evaporation takes place. When evaporation takes place during the hydration period, the actual obtainable degree of hydration will be even lower and it will be the lower, the more water is evaporated. In figure 9 the parameter β_{max} expresses how big the degree of hydration can be in relation to β_0, when evaporation takes place, i.e. β_{max} = 1 at no evaporation.

Figure 9: Structure density parameter $V_{cap=0}$ and maximum degree of hydration β_{max} caused by evaporation

Test No.	$V_{cap=0}$	Maximum degree of hydration β_{max}
1	0.908	0.96
2	0.918	0.98
3	0.923	1.00
4	0.804	0.74
5	0.893	0.93
6	0.914	0.98
7	0.799	0.72
8	0.917	0.98
9	0.884	0.91
10	0.948	1.05
11	0.914	0.98
12	0.921	0.99
13	0.901	0.95
14	0.912	0.97
15	0.916	0.98
16	0.903	0.95
17	0.911	0.98
18	0.920	1.00

Figure 9 shows that the maximum degree of hydration β_{max} was bigger than 0.90 in all tests, except in the tests Nos. 4 and 7. In these two tests no curing was used (they had a free surface), the evaporation was high and the maximum degrees of hydration were 0.74 and 0.72.

As mentioned previously (section 2.3) four types of measurements were made to evaluate the effect of the different curing methods. The results of these measurements were graphed as a function of the structure density parameter $V_{cap=0}$ in order to test the hypothesis mentioned above.

In order to make it possible to draw a common conclusion based on all the measurements, the ranges of the results in each type of measurement were normalised into the range 0-100 (as a parameter to describe the crack formation was used an average of the normalised parameters for surface cracks and paste cracks). Then four linear regression analyses were performed with the normalised values of the structure density parameter $V_{cap=0}$ as an independent variable and each of the normalised results of the four types of measurements as dependant variables. The regression analysis included only the laboratory tests, because the evaporation was not measured in the six on site tests, but the results from the analysis were used on the results from the on site tests too.

The results of these calculations were:

	Correlation coeff. (R^2)	Regression slope
Chloride penetration rate	0.84	-1.10
Carbonation depth	0.52	-0.87
Crack formation	0.37	0.56
Capillary suction	0.10	0.29

The correlation coefficients demonstrate, that only the chloride penetration rates and to some extent the carbonation depths can be said to be correlated to the structure density parameter $V_{cap=0}$.

However, a weighted sum of all four parameters has been calculated, in which the slopes of the regression lines were used as the weighting coefficients, see figure 10.

As an example the WSP of test No. 1 has been calculated as follows:

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

Figure 10: Summary of measurements, normalised parameters (range 0 - 100) (WSP = weighted sum of parameters)

Test no.	$V_{cap=0}$	Cracks	Chloride pen.	Capillary abs.	Carbo- nation	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

This weighted sum has been used to rank the tests, figure 11.

Figure 11. 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 at 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 compound
12	12	0.99	Mould in 3 Mdays + Foam-matt
13	11	0.95	Foam-matt after 5 Mh
1-Vertical	5	-	Mould and form liner in 3 Mdays, plastic 98-113 Mh
17	4	0.98	Mould in 3 Mdays + Curing compound
3-Vertical	1	-	Timber form work in 3 Mdays, curing compound, plastic 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-Vertical	-20	-	Mould in 3 Mdays, curing compound, plastic 98-113 Mh
1-Horizontal	-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-Horizontal	-55	-	Curing compound after 7 Mh, plastic 20-88 Mh
2-Horizontal	-69	-	Curing compound 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.

6. Guidelines

A result of this project are guidelines for curing concrete. The requirements on curing of concrete are included in a Danish draft proposal standard "Execution of Concrete Structures" [march, 1997] (Danish title proposed: DS 482 "Udførelse af betonkonstruktioner").

Two types of demands exist: Demands on the initial period from casting until the curing must be started, and demands on the length of the curing period.

The demand on the starting time is defined in two ways:
- Only a fixed number of hours is allowed to elapse before curing must be started
- Only a certain amount of water is allowed to evaporate before curing is started.

The demand on the length of the curing period is also defined in two ways:
- A fixed number of hours must elapse before curing is allowed to be stopped
- A minimum degree of hydration must be obtained, before curing is allowed to be stopped, calculated from measurements of the adiabatic heat development.

The guidelines include examples on how curing can be planned and documented.

7. Further Investigations

When the 24 curing tests were planned it was assumed that the degree of hydration of the concrete would vary a lot, so that it would be possible to put forward guidelines for the minimum degree of hydration required to obtain a sufficient quality of the concrete surface. However the results showed to be split up into two groups. In 22 out of 24 laboratory tests the maximum degree of hydration, that could be obtained, was above 90%. Only in the two tests without any curing, were the maximum degrees of hydration lower than 90% (about 73%). In order to cover the range below 90% it would be interesting to perform tests with curing methods, which can obtain degrees of hydration between 75% and 90%.

As the degree of hydration depends both on the evaporation of water before the curing is started, and on the length of the curing period, it might be interesting to investigate further to what extent the length of the initial period will influence the demands on the length of the curing period.

In the actual curing tests the maximum degree of hydration is determined as the point, where the capillary water content becomes 0. If water is added to the surfaces, e.g. as rain, some water might be absorbed in the concrete and the hydration process might be continued to give a more dense structure of the surface. Therefore it would be interesting to perform further tests on the specimens already tested.

The degree of hydration of the concrete depends considerately on the amount of capillary water. So it would be interesting to study the mechanism of water flow in the concrete. If the water only moves slowly from the interior parts of the concrete to the surfaces, only the uttermost layer of the concrete will be influenced by the curing method. If on the other hand the water moves quickly to the surface, most of the concrete structure will be influenced by the evaporation caused by a poor curing method. Such considerations might be used to establish requirements on the starting time of curing based on other parameters than the binder composition and the evaporated amount of water.

Experiments with spraying a curing compound directly on the concrete surface, before the concrete has hardened, have shown to give tight surfaces. This is surprising, as the manufacturers of curing compounds normally suggest to spray the curing compounds only on hardened concrete surfaces. It would be interesting to investigate, if this experience is of general nature, and what this would demand on the curing compound in such cases.

Tests with concrete in mould for 24 maturity hours have indicated that curing for 24 maturity hours might be sufficient. It might be interesting to investigate, if this is a general experience by testing different types of concrete.

8. List of Literature

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