Curing of High Quality Concrete

Marlene Haugaard, Project Manager, B.Sc.
DTI Building Technology
P.O. Box 141
DK-2630 Taastrup

Kirsten Riis, M.Sc.
DTI Building Technology
P.O. Box 141
DK-2630 Taastrup

ABSTRACT

24 curing tests were performed on high quality concrete. The first 18 tests were conducted under controlled climate conditions in a laboratory, and the 6 last tests were performed on a bridge construction. The curing tests vary in the starting time of the curing process, the curing period, and type of membrane.

The following measurements were performed on the concrete surface to determine the concrete surface density after a given curing method.

- Chloride penetration according to ASTM C 1202
- Surface carbonation depth according to NT Build 357
- Crack formation according to TI-B 5
- Capillary water absorption according to TI-B 25

The tests have been evaluated and three remarkable results have been found. Firstly, the tests show that you cannot 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 curing compound sprayed on the concrete surface after only 2 hours of maturity after mixing the concrete gives a tight concrete surface. Thirdly, only few micro cracks had been obtained in the concrete that had not been cured at all. This means that if no micro cracks are found in the concrete surface with low w/c-ratio, it may indicate that the concrete has not been cured properly.

Key words: Concrete, curing, quality, surface, test methods.

1. INTRODUCTION

In the Danish Road Directorate's research Programme: High Performance Concrete - The Contractor's Technology, in Danish "Højkvalitetsbeton - Entreprenørens Teknologi" abbreviated to HETEK, one project part was curing. The purpose of this project part was to investigate the effect of different curing methods on the quality of the concrete surface. The curing methods used were either extreme e.g. water curing, no curing, curing in mould for a long period of time, or commonly used curing methods such as covering the surface with diffusion tight materials or spraying with curing compound. The project was finished in Spring 1997.

An important property of high performance concrete with a w/c-ratio below 0.45 is the water content which 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 the sufficient strength and stiffness of the concrete have been obtained. So it is important to cure the surface of the fresh concrete and protect it from evaporation efficiently to reach a sufficient state of hydration.

The evaporation from the concrete surface 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.

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

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

Investigations [Lundberg, 1994] have indicated that keeping the concrete for a shorter period in a 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 demands on curing is only one of many for concrete production it is important to study the effect of the different curing methods to make it possible for the contractors to choose the curing method which best adapts to each individual casting process.

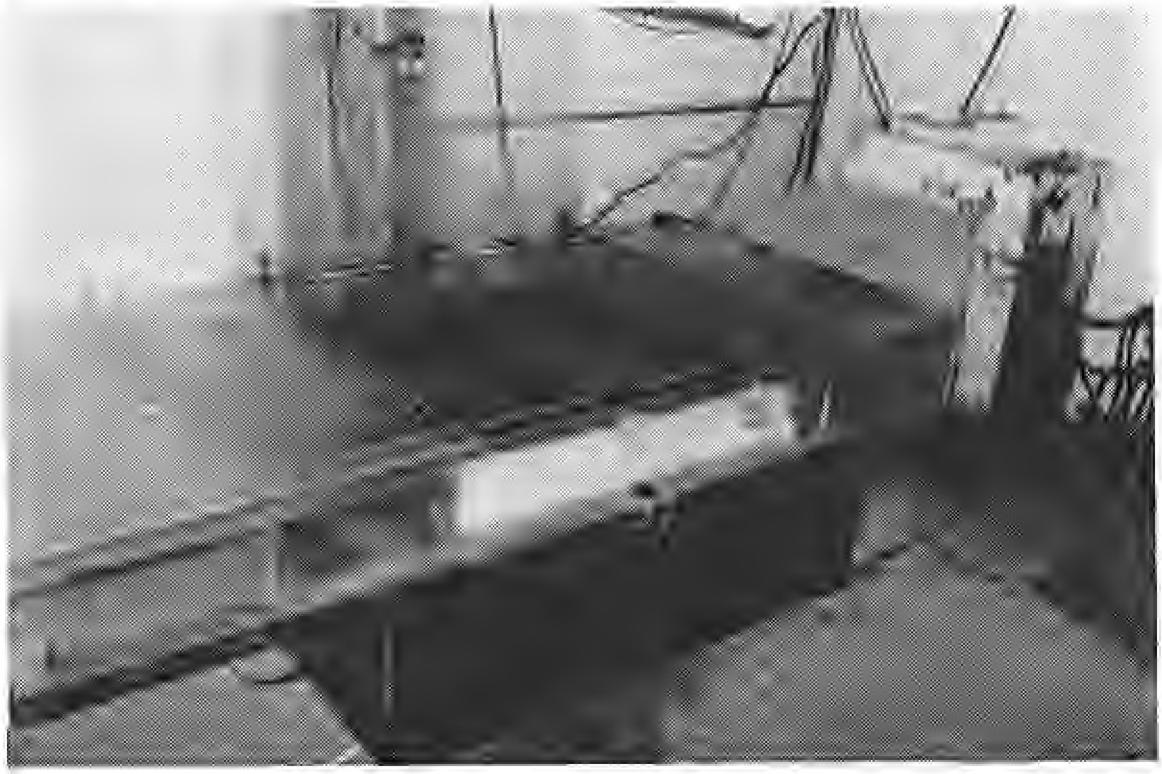
2. TESTS

The report HETEK Curing, State of the Art, described the problems concerning curing of concrete. On the basis of this report different curing methods including commonly used methods and some extreme variants were selected for testing.

24 curing tests were performed to determine the density of the concrete surface in relation to the chosen curing method. The first 18 tests were conducted under controlled climate conditions where the temperature, the relative humidity, and the wind velocity were measured and were approximately constant over a period of 10 maturity days. The maturity days were calculated from the measured temperatures. The last 6 tests were performed on site on a bridge structure where the climate conditions were measured continuously.

5 main types of curing methods were used as follows:

- Curing of the concrete surface in a closed mould for a period of 1-3 maturity days combined with either non-treated surface, adding of curing compound, or sealing of the surface with a matt of 10 mm extrude polyethylene foam.
- Curing of the concrete surface either by adding curing compound, water curing, or sealing of the surface with a matt of 10 mm extrude polyethylene foam. The curing was established at the time where the surface was mat dry which is approx. at the time of setting.
- Curing of the wet concrete surface either by adding curing compound or sealing the surface with a transparent plastic foil.
- Curing of the concrete surface in moulds for a period of 10 maturity days.
- No curing of the concrete surface, meaning curing in controlled climate conditions.



The curing compound was a product based on water and ester and has an efficiency of 84% determined according to the test method TI-B 33.

For all laboratory tests water proof plywood, 18mm moulds were used.

To determine the importance of the moulds used, curing test on site were performed with plywood form work, timber form work, and form liner on plywood form work.

Table 1. Concrete recipes

Materials	Description	Type 1 [kg/m³]	Type 2 [kg/m³]
Cement	Low-alkali Sulphate resistant cement CEM I 42,5 (HS/EA/≤2)	285	274
Fly ash	Danaske	60	61
Silica fume	Elkem/Powder	12	16
Water	Water	126	134
Fine aggregate	RN-Avedøre, 0-4/A	758	733
Coarse aggregate	Rønne Granit 4-16/A	-	679
Coarse aggregate	Rønne Granit 8-16/A	535	-
Coarse aggregate	Rønne Granit16-25/A	565	453
Air entraining	Complast 316 AEA 1:5, Fosroc	1,1	1,6
Plasticizer	Conplast 212, Fosroc	1,4	1,1
Super-plasticizer	Peramin F, Fosroc	2,9	1,8

To each of the curing test in the laboratory one specimen with the size 400 x 400 x 100 mm was cast with concrete delivered from a ready to mix plant. Two types of concrete were used.

The concrete recipes are shown in Table 1 (both concrete mixes are air entrained). Both concrete types are made from the same materials and have a maximum equivalent w/c-ratio of respectively 0.40 and 0.45. The type 1 concrete was used for most of the laboratory tests and the type 2 was used for the on-site-tests and a few laboratory tests.

The laboratory tests were conducted in a climate controlled wind tunnel. The climatic conditions were: a temperature at 20°C, a relative humidity at 65% and a wind velocity at 3,6 m/s. The tunnel included a scale for continuos recording of the weight changes of the test specimens - changes caused by evaporation from the concrete surface. In order to evaluate the effect of the different curing methods four types of measurements were made:

- Chloride penetration according to ASTM C 1202
- Surface carbonation depth according to NT Build 357
- Crack formation according to TI-B 5 (The total crack length in the utmost 2.5 mm of the surface and the paste crack in the internal structure were measured.)
- Capillary water absorption according to TI-B 25 (The degree and the time of saturation were determined.)

Table 2 shows the test results of each of the curing tests:

Table 2. Test Results

Chloride penetration ASTM at 28th maturing day C1202 [Coulombs]	Carbonation depth NT Build 357 at 3 months maturing Mean [mm]	 Max [mm]	Crack formation analysis TI-B 5 Total length of cracks [mm]	 Internal paste cracks [No./mm²]	Capillary water absorption TI-B 25 Degree of saturation [%]	 Duration of saturation [Hours]	Curing method	Test No.
1013	3	5	12.3	0.29	61	5.6	Mould (3)	1
1049	3	5	7.4	0.27	63	8.1	Mould (3)+C	2
2139	10	12	16.4	0.12	53	4.0	Mould (10)	3
>4000	25	26	2.9	0.05	48	5.3	None	4
1717	11	13	1.2	0.06	43	3.5	Mould (1)	5
1556	8	9	7.7	0.15	42	3.2	Mould (1)+C	6
>4000	22	25	0.0	0.02	40	7.3	None	7
951	0	3	1.4	0.09	44	17.6	Mould (3)+C	8
1710	8	10	15.5	0.05	41	6.6	At setting time: C	9
985	5	7	17.7	0.30	54	2.3	At setting time: Water	10
1084	8	10	5.2	0.04	61	3.6	Mould (1) + Matt	11
1059	5	9	8.8	0.09	56	3.4	Mould (3) + Matt	12
1463	3	4	10.1	0.18	50	4.0	At setting time: Matt	13
985	0	0	4.6	0.04	43	15.2	Before setting time: C	14
1098	0	7	8.6	0.14	51	2.8	Mould (3) + C	15
1015	0	3	6.2	0.09	52	3.2	Before setting time: C	16
1534	7	12	9.9	0.14	58	9.3	Mould (3) + C	17
1360	20	24	12.2	0.19	71	1.6	Before setting time: P	18
1475	10	13	4.4	0.29	45	2.4	Before setting time: P	19
2103	14	15	0.0	0.22	50	7.5	Before setting time: C	20
2671	3	6	0.9	0.31	42	2.7	At setting time: C	21
1421	0	0	5.7	0.14	41	2.4	Mould + form liner (3)	22
1904	8	10	4.9	0.36	41	3.6	Mould (3) + C	23
1352	0-3	4	3.5	0.22	37	2.0	Timber mould (3) + C	24

The first 16 tests are cast with concrete type 1. The last 8 tests are cast with concrete type 2. C is curing compound. P is plastic. (x), x is the number of maturity days in the mould.

Test No. 7, 8, 15 and 16 is a verification of test No. 4, 2 and 14 performed at a lower relative humidity at approximately 45% in the laboratory. Test No. 17 is a verification of test No. 2 but with concrete type 2. Also test No. 18 to 24 were performed with concrete type 2.

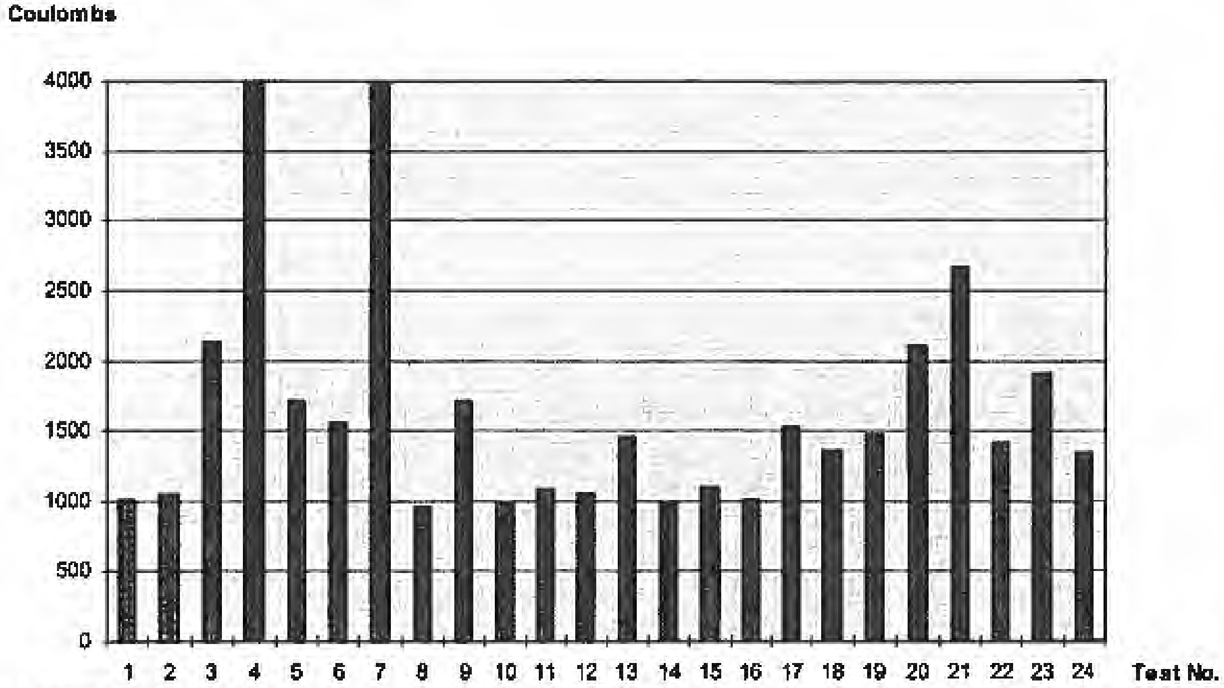


Figure 1 Chloride Penetration

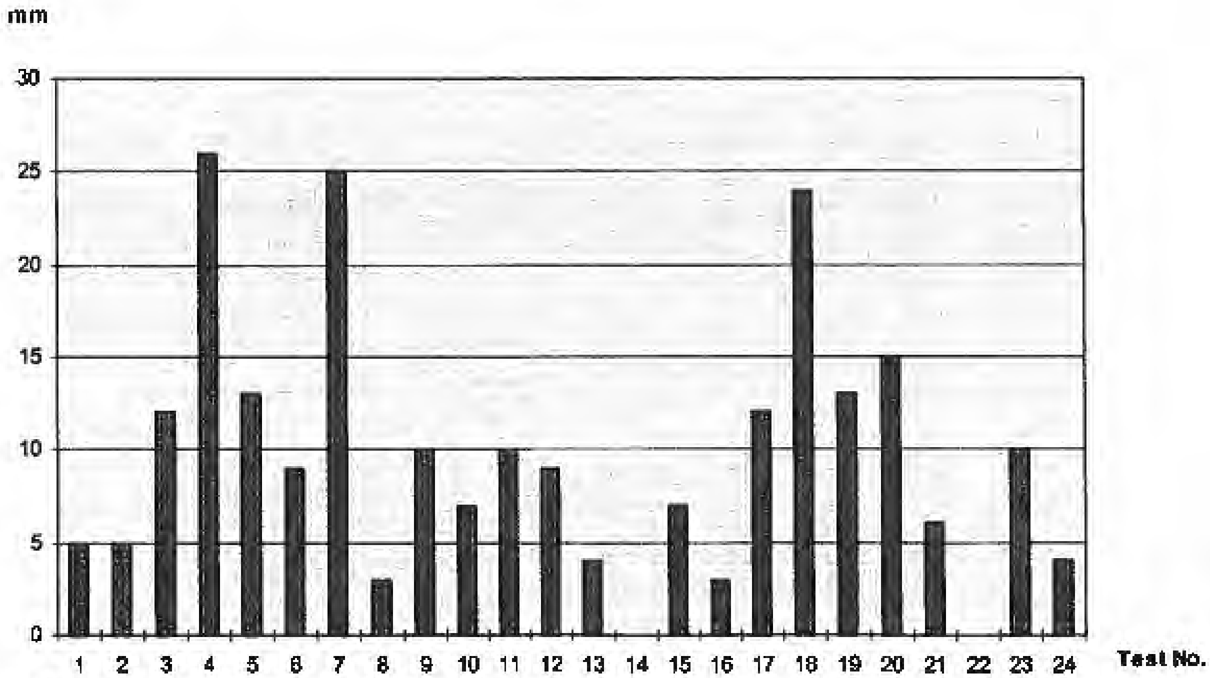


Figure 2 Carbonation depth max.

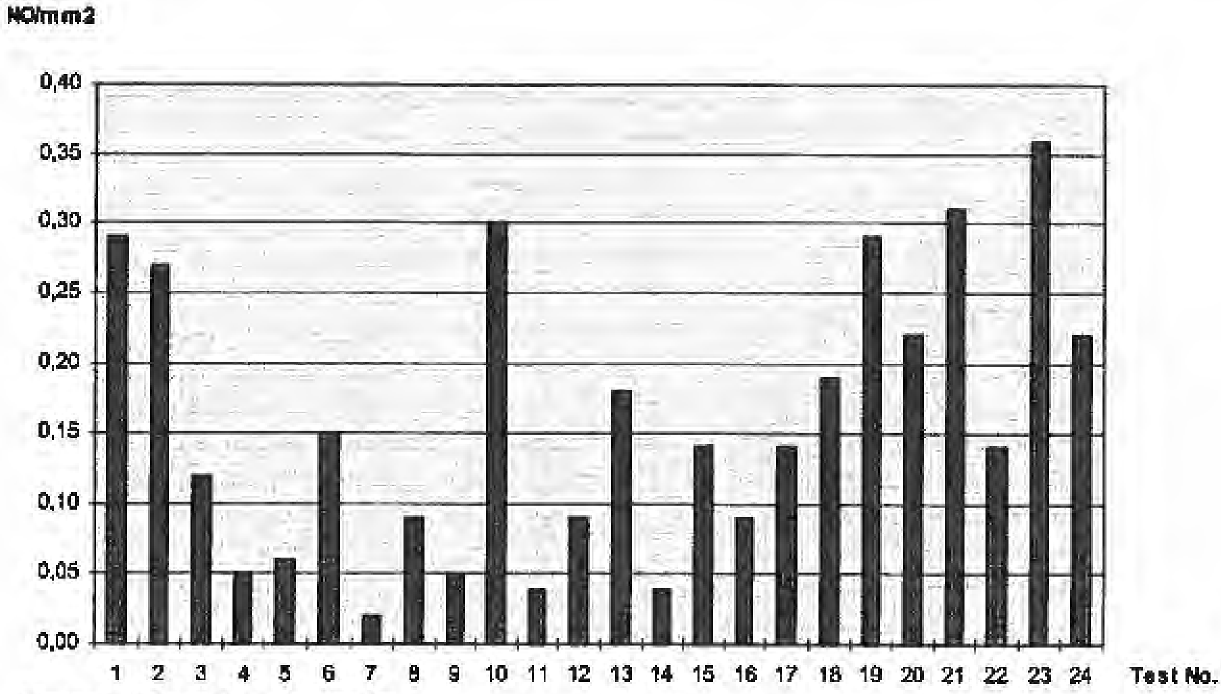


Figure 3 Internal paste cracks

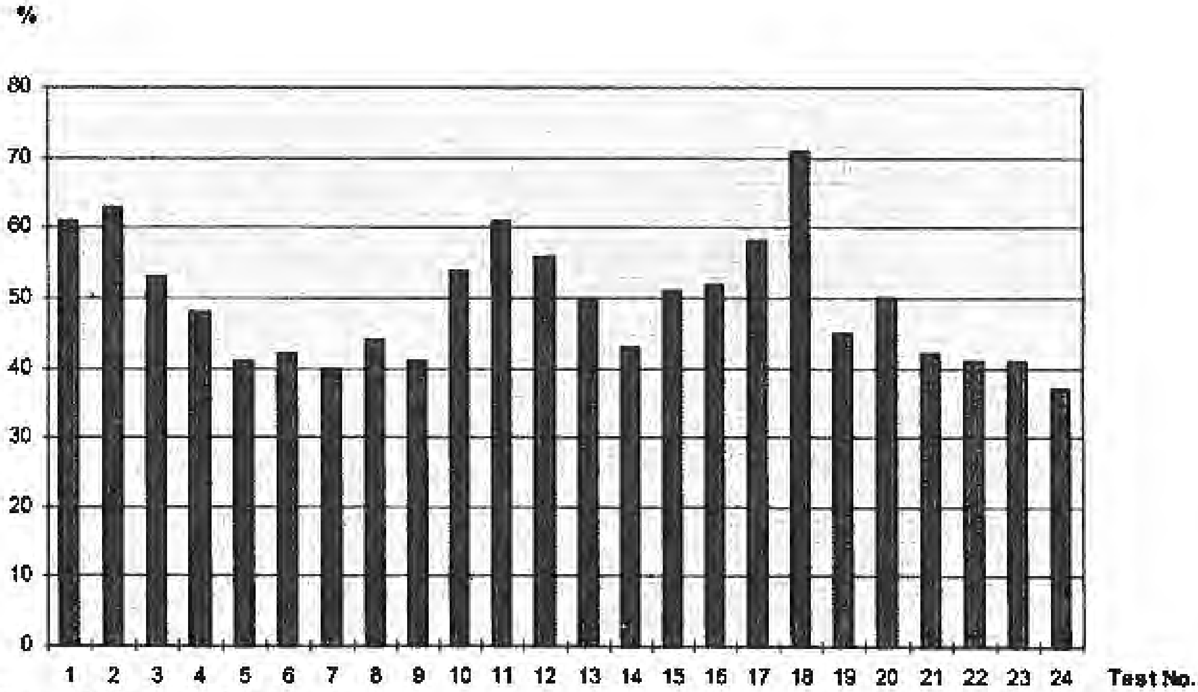


Figure 4 Degree of saturation

3. EVALUATION OF THE RESULTS

The basic hypothesis is that parameters as chloride penetration rate, surface carbonation depth, crack formation, and capillary water absorption depend on the structural density of the cement paste. The more dense the concrete is the more impermeable the concrete is.

In a concrete with a low w/c -ratio (< 0.45) only a certain fraction of the cement ,β_0, 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 the degree of hydration will decrease with the increase of water evaporated. In Table 4 the parameter β_{max} expresses how high the degree of hydration can be in relation to β_0, when evaporation takes place.

In order to investigate the hypothesis, a structure density parameter called $V_{cap=0}$ was calculated for each curing test. $V_{cap=0}$ represents 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 mix design and the amount of water evaporated during the curing, which runs till 10 maturity days after casting. The calculation is based on the theory of Powers [Powers, 1948].

The results of the four measurements of the parameter chloride penetration, surface carbonation depth, crack formation and capillary water absorption were graphed as a function of the structure density parameter $V_{cap=0}$ in order to test the hypothesis. In order to make it possible to draw a general conclusion based on all the measurements the ranges of all the results for each type of measurement were normalised into the range 0-100 (as a parameter to describe the crack formation an average of the normalised parameter for surface cracks and paste cracks was used). 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 dependent variables. The regression analyses included only the laboratory tests because the evaporation was not measured in the six curing tests on the bridge structure, but the results from the analyses were used on the results from the measurements on the bridge structure. The results of these calculations are shown in table 3.

Table 3 Result of regression analyses

	Correlation coefficient (R^2)	The slope of the regression curve
Chloride penetration	0.84	-1.10
Surface carbonation depth	0.52	-0.87
Crack formation	0.37	0.56
Capillary water absorption	0.10	0.29

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

However, a weighted sum of all four normalised parameters, WSP, has been calculated in which the slopes of the regression lines were used as the weighting coefficients, re. Table 4.

As an example the WSP of the first test (see normalised parameter in Table 3) has been calculated as follows:

$$WSP = 2 A (-1.10) + 13 A (-0.87) + 75 A (0.56) + 95 A(0.29) \cdot 56.$$

Table 4. Summary of measurements, normalised parameters together with the structure density

$V_{cap=0}$	ASTM C1202	NT Build 357	TI-B 5	TI-B 25	WSP	$\exists_{max}$	Curing method	Test No.
73	2	13	75	95	56	0.96	Mould (3)	1
80	3	13	59	100	47	0.98	Mould (3) +C	2
84	39	41	63	54	- 27	1.00	Mould (10)	3
-4	100	100	10	29	-183	0.74	None	4
63	25	44	12	17	-54	0.93	Mould (1)	5
77	20	29	43	22	-17	0.98	Mould (1) +C	6
1	100	93	2	33	-180	0.72	None	7
79	0	2	16	52	22	0.98	Mould (3) +C	8
57	25	26	51	29	-13	0.91	At setting time: C	9
100	1	21	91	41	43	1.05	At setting time: Water	10
78	4	33	21	68	-2	0.98	Mould (1) + Matt	11
82	4	20	37	41	12	0.99	Mould (3) + Matt	12
68	17	15	53	46	11	0.95	At setting time: Matt	13
76	1	2	18	56	23	0.97	Before setting time: C	14
79	5	0	43	27	27	0.98	Mould (3) + C	15
70	2	0	30	30	23	0.95	Before setting time: C	16
75	19	22	47	59	4	0.98	Mould (3) + C	17
81	13	79	38	52	-47	1.00	Before setting time: P	18
-	17	41	53	14	-21	-	Before setting time: P	19
-	28	59	31	24	-69	-	Before setting time: C	20
-	56	19	36	31	-55	-	At setting time: C	21
-	15	0	36	8	5	-	Mould + form liner (3)	22
-	31	29	64	14	-20	-	Mould (3) + C	23
-	13	9	42	0	1	-	Timber mould (3) + C	24

C is curing compound. P is plastic. (x), x is the number of maturity days in the mould.

From the weighted sum of parameters, WSP, it is found that two of the curing methods differ from the others in that they are ranked with very low values of WSP. These two tests were performed with no curing.

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

1. The 12 curing methods with the highest value of the WSP:
   - in moulds for 3 maturity days combined with or without curing
   - water curing
   - curing compound on the fresh concrete surface
   - foam-matt added at the time of mat-dry concrete surface

2. The 10 curing methods with average values of WSP:

- curing compound added at the time of mat-dry concrete surface
- in moulds for 1 maturity day combined with or with out curing
- in moulds for 10 maturity days
- plastic foil on the fresh concrete surface

Results of two of the curing tests performed on the bridge construction (in moulds for 3 maturity days combined with curing compound and curing compound on the fresh surface) do not confirm this pattern, as their values of the WSP are in group no. 2 in stead of group no. 1.

4. CONCLUSION

The four parameters chloride penetration, carbonation depth, crack formation analysis and capillary water absorption have been measured to evaluate the effect of the various curing methods.

The basic hypothesis is that the measured parameters depend on the structural density of the cement paste. In order to investigate the hypothesis, a structure density parameter called $V_{cap=0}$ was calculated for each test. $V_{cap=0}$ represents 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.

From the results the following conclusions can be made:

- Correlation between the structure density parameter $V_{cap=0}$ and the chloride penetration.
- Weak correlation between the structure density parameter $V_{cap=0}$ and the surface carbonation depth.
- Weak correlation between the structure density parameter $V_{cap=0}$ and the crack formations in the surface and in the cement paste.
- No correlation between the structure density parameter $V_{cap=0}$ and the parameters determined in the capillary water absorption.

Some of the curing tests were performed more than once. They have shown almost the same results, and this indicates a good reproducibility in the laboratory. The reproducibility and repeatability has been evaluated as food in other investigations [Berrig, 1992].

The two curing tests with plastic foil on the fresh concrete surface show almost the same results in spite of the different climatic conditions in the laboratory and in the field. Compared to the results from the tests where curing compound was used on the fresh concrete surface, the tests with plastic foil have shown lower values. This indicates a lower efficiency of plastic foil than of curing compound presumably caused by the fact that it is difficult to keep the plastic foil tight to the concrete surface even in laboratory tests. This is indicated by the weight loss measurements.

A field test with form liner for 3 maturity days has shown the same results as a field test with timber form work for 3 maturity days combined with adding of curing compound. This indicates that use of form liner, which is expensive, is not better than the old-fashioned practise of using timber form work, which is cheaper. Both field tests with form liner or timber form work combined with adding of curing compound have shown slightly higher values than the field test with plywood form work for 3 maturity days combined with adding of curing compound. The result variations are minor. It must of course be remembered that these comments are based on a few results.

It is also remarkable that the laboratory tests with the curing compound on the fresh concrete surface have shown high values and the comparable field test has shown a rather low value. Nevertheless, no explanation of this difference has been found.

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

The results of the curing tests are that the hypothesis has been confirmed for the types of concrete with fly ash, micro silica, and a low water/cement-ratio.

Three remarkable achievements are:

1. Curing in mould for 10 maturity days has resulted in a low rating, as also seen in a previous test. [Lundberg].

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

3. Only few values of crack formation have been obtained in concrete without curing.

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

The remarkable results with curing compound added to the fresh concrete surface must be investigated further in a test series with different curing compound types and concrete types. The tests with curing in moulds for 10 maturity days do not show better results than those with mould for 3-5 maturity days. This confirms a previous result, and must lead to less restricted requirements for the total curing time, as already seen in project specifications i.e. the Øresund Link.

It must be emphasised that the low values of micro crack formation in concrete without curing at all are in accordance with theoretical considerations that the micro cracks in concrete with a w/c-ratio below 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 concrete surface with a low w/c-ratio it may indicate that the concrete has not been cured properly.

The over-all conclusion is that the concrete surface must be protected against evaporation to ensure a sufficient dense cover of the concrete.

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