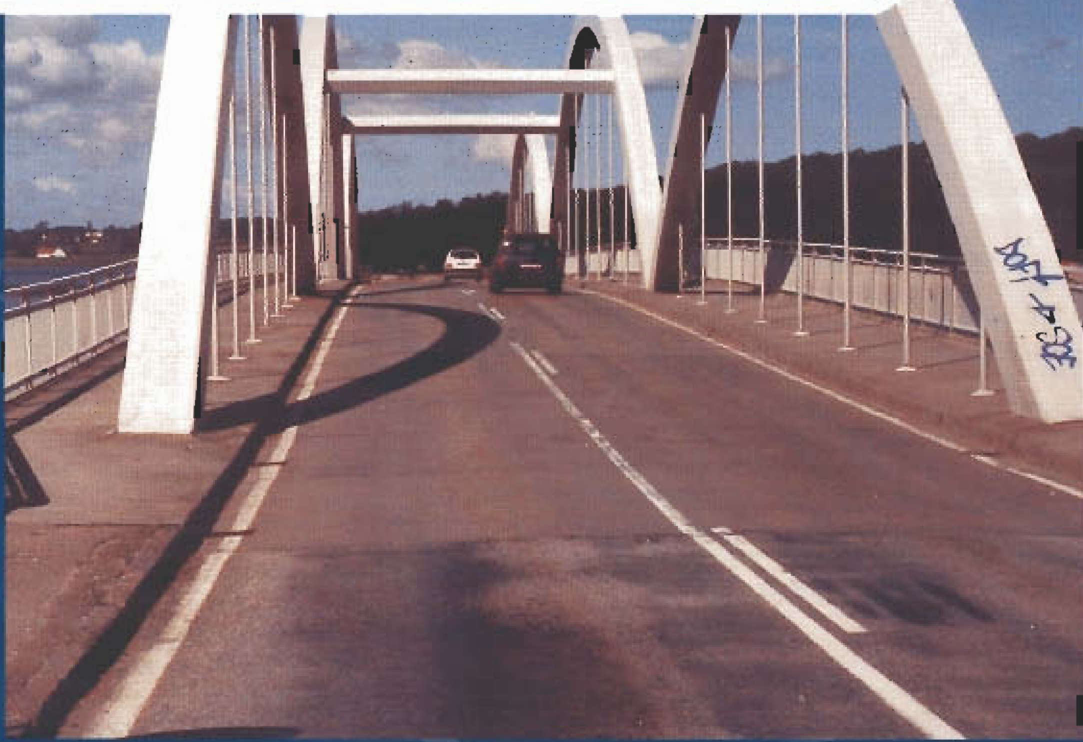
HETEK

Method for Test of the Frost Resistance of High Performance Concrete

Performance Testing versus In Situ Observations



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Abstract

26 Danish concrete structures of varying age, exposure conditions, compositions, and visual appearance have been investigated by several methods in the search for possible correlation between accelerated frost testing results in the laboratory and actual in situ behaviour regarding frost attack. Two frost testing methods, modified Borås testing, and modified ASTM C 666, Procedure A, as well as an alternative rapid supplementary test, determination of the pore protection ratio, have been included in the test programme.

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Data Reports

Investigation data for all site inspections and laboratory tests on the selected structures are reported in detail in separate data reports. The data report is printed in seven copies. Two of these are kept at the Danish Road Directorate.

Data Reports:

1 Site-Inspection of Proposed Sampling Sites and Classification of Environment, Dansk Betoninstitut A/S and DTI, November 1996

2 Work Plan for Handling of Cores, Dansk Beton Teknik A/S and Dansk Betoninstitut A/S, November 1996

3 Description of Cores (in Danish), Dansk Betoninstitut A/S, November 1996

4 + 5 Moisture Tests and Sorption Characteristics, Dansk Beton Teknik A/S, November 1996

6 Air Void Analyses, Dansk Beton Teknik A/S, September 1996

7 Petrographic Analysis of 25 concrete cores, Dansk Betoninstitut A/S, October 1996

8 Frost Test, Borås Method on cores from 25 concrete structures, DTI Building Technology, October 1996

9 Frost Test, modified Borås method, DTI Building Technology, November 1996

10 Frost Test, modified ASTM C 666, Procedure A, Dansk Beton Teknik A/S, January 1997

11 Macro analysis of frost tested samples, Dansk Betoninstitut A/S, February 1997

1 Introduction

The Danish Road Directorate has made a research and development contract with seven consortia and individual companies. The subject of the contract is the establishment of guidelines for the execution of concrete structures with 100 years' service life, focusing on the technology of the contractor. Experience from large construction works proves that the execution phase is important to the achievement of the requested durability of concrete structures exposed to an aggressive environment.

The development contract is financed by the Danish Agency for Development of Trade and Industry which demands that the task be defined, contracted and managed by a public agency, in this case the Road Directorate.

Task 2 of the development contract:"Test Methods for determining the Frost Resistance of High Performance Concrete", was awarded to a consortium consisting of Dansk Beton Teknik A/S, Dansk Teknologisk Institut, and Dansk Betoninstitut a/s. High performance concrete is defined as concrete with an expected service life of 100 years in an aggressive environment [VD, 1995]. The consortium has implemented the following definitions of 'High Performance Concrete':

> Concrete that can last for 100 years in an aggressive environment, having an equivalent w/c-ratio of 0.35-0.45, and complying with the present Danish specifications regarding materials, mix composition etc.

The first activity of Task 2 was a State-of-the-art Report. As basis for the future work in Task 2 this report included an evaluation of selected test methods based on review of existing national and international knowledge [Laugesen et al, 1996]. Based on this study and the supplementary research [Geiker et al, 1996] two frost testing methods (the Borås method, and ASTM C 666, Procedure A) as well as a modification of the Borås method were chosen for further investigations regarding their ability to predict the frost resistance of high performance concrete structures. Furthermore, an alternative rapid supplementary test, determination of the pore protection ratio, was included in the programme [Vuorinen, 1984].

1.1 Objectives

The purpose of this investigation is to provide information on the applicability of selected accelerated frost testing methods

- The Borås method, SS 13 72 44, 1995 (III)
- A modified Borås method (conditioning at 50°C for 14 days followed by 14 days resaturation)
- A modified ASTM C 666, Procedure A method (reduced specimen length)

for estimation of the frost resistance of concrete structures by comparing actual performance of a number of structures with results of laboratory frost testing, environmental exposure condition, and material characteristics.

Also, the applicability of a supplementary method for evaluation of the frost susceptibility

- The pore protection ratio

is to be investigated by comparing test results with the behaviour of the structures.

Furthermore, the present activity shall provide a basis for the proposal of tentative acceptance criteria for frost testing of high performance concrete as well as a basis for the preparation of guidelines for frost testing of such concrete.

2 Conclusions

Two hundred and four cores from 26 Danish concrete structures of varying age (1953-1985), exposure condition, composition, and visual appearance have been investigated by several methods in the search for possible correlation between accelerated frost testing results in the laboratory and the actual in situ behaviour regarding frost attack on the concrete. Structures selected are bridges (decks, edge beams, barriers, columns, walls) and pavements.

The investigation includes testing of Portland cement concretes (w/c-ratio generally 0.35-0.45) with and without fly ash and silica fume.

The exposure of the structures has been classified in three exposure classes:

1: Structures exposed to frost and water, with or without salt
2: Structures exposed to frost and sometimes to water, with or without salt
3: Vertical surfaces exposed to frost, but rarely to water and not to salt

Frost damage was assessed by visual in situ inspection and by petrographical examination of concrete cores. The damage was ranked in four classes 0, 1, 2, or 3, from none to much frost damage. It appears from the results of the present project that the - amount of in situ frost damaged structures varies in the different exposure classes. Concrete structures of exposure class 1 have a high amount of freeze/thaw damage. For the exposure class 1, 5 out of 14 structures are damaged, whereas none of the 7 and 5 structures in environmental class 2 and 3, respectively, shows frost damage.

From each of the structures, eight cores were drilled from a small area assumed to be representative and of a homogeneous concrete quality. The testing was in general performed on undamaged concrete taken from the interior of the structures. The environmental exposure, the surface orientation and the visual appearance of the coring site was recorded, ref. above.

Six of the cores from each structure were tested using three different methods of possible relevance to frost resistance, two based on accelerated freeze/thaw performance testing, and one based on moisture ingress testing. The methods were:

- The Borås freeze/thaw test (standard and modified conditioning)
- The ASTM C 666-A freeze/thaw test (modified)
- The pore protection ratio test (Vuorinen)

The remaining two cores from each structure were analyzed with respect to:

- Air void structure
- Concrete macrostructure and microstructure (fluorescence impregnated cut sections and thin sections)
- Moisture condition: Relative humidity, degree of capillary water saturation, and moisture content

The following conclusions are based on the outcome of a comparison between assessment of the in situ condition and the outcome of the laboratory testing.

2.1 Conclusions on the Borås Testing

The Borås test method should primarily be used for the assessment of the probability of frost scaling.

Based on the present results, the following requirement to specimens from cores drilled from concrete structures and tested according to the standard Borås method could be argued relevant:

Exposure class 1: $m_{56} < 0.5$ kg/m^2

The results indicate that the requirement for exposure class 1 might be increased to 1 kg/m^2 after 56 freeze/thaw cycles. However, this should be further documented. The probability of accepting/rejecting concrete with improper/proper in situ performance should be selected by the owner.

Requirements to the so-called acceleration factor, $m_{56} / m_{28} < 2$ has been omitted here. The assumed low probability of accepting concrete with low freeze/thaw resistance should be further documented.

Too few data on damaged structures (damage degree 2-3) are available for conclusions regarding requirements for concrete structures in exposure classes 2 and 3. However, based on evaluation of the possible exposure conditions in situ we tentatively suggest the following requirement applied for drilled cores:

Exposure class 2: $m_{56} < 1.0$ kg/m^2

Based on the limited data available, the modified Borås method, including a severe drying during conditioning, seems to cause less scaling than the standard Borås method and not to provide sufficient differentiation between different concrete qualities. The modified Borås method is not recommended.

No firm conclusions regarding the possibility of evaluating internal damage by measurement of length change during Borås testing can be made based on the present results.

2.2 Conclusions on the ASTM C 666, Procedure A (Modified) Testing

The ASTM C 666-A test method should primarily be used for the assessment of the probability of internal frost damage. The method does presently not include salt exposure.

Based on the present investigation it is evaluated that the modified ASTM C 666-A test method is relevant for the testing of the frost resistance of concrete structures in exposure class 1 applying the following requirement to cores drilled from the structures:

Exposure class 1: Expansion after 300 freeze/thaw cycles < 0.1%

Expansion in excess of 0.1% is accompanied by visible crack formation in laboratory specimens. Based on this - and in spite of 0.1% expansion being eight times the strain capacity - it is presently evaluated as an applicable limit.

The probability of accepting/rejecting concrete with improper/proper in situ performance should be selected by the owner, e.g. by requiring another number of freeze/thaw cycles.

The present data are too limited to draw any firm conclusions regarding the possibility of estimating frost resistance of exposure class 2 or exposure class 3 structures by the modified ASTM C 666-A test. However, based on the assumption that class 2 and class 3 exposure does not cause moisture saturation of the concrete, the method is not regarded relevant for these exposure conditions.

2.2.1 Modifications of ASTM C 666, Procedure A

The following modifications to the ASTM C 666-92, procedure A test method were applied in the HETEK project and are suggested documented further for future testing of concrete structures:

* Length change measured; this appears to have been an adequate and more precise measure than measurement of dynamic E-modulus
* Three samples per structure were tested in the present project.The required number of samples for future testing should be further documented
* Samples of length 135-140 mm (corresponding to a core length of at least 200 mm) were used in the project in stead of 279-406 mm. The present, but limited results indicate that this length is sufficient
* No casting joints should be present in samples
* Reinforcement bars in the samples appeared to have no influence on the test results

2.3 Conclusion on the Pore Protection Ratio Testing

The testing of pore protection ratio is recommended used as a supplementary test for assessment of the probability of frost damage in situ. The critical pore protection ratio depends on the w/c-ratio of the concrete and the exposure conditions.

Although, there appears to be a large probability of rejecting a proper concrete we tentatively suggest the following requirement for the pore protection ratio in cores drilled from concrete structures in exposure class 1:

Pore protection ratio > 0.25

Further research is needed to confirm this, especially for low w/c-ratio concrete.

Based on the present scarce results, it is evaluated that the frost resistance of exposure class 2 or exposure class 3 structures are not well described by the pore protection ratio. However, the present data are too limited to draw any firm conclusions.

2.4 Conclusions on Correlations between Test Results of the accelerated Frost Testing and the Pore Protection Testing

With the application of the suggested requirements to frost resistance of drilled cores from concrete structures in exposure class 1:

* ASTM C 666-A (modified): Less than 0.1% expansion after 300 cycles
* Borås (III): Less than 0.5 kg/m^2 after 56 freeze/thaw cycles

it appears that the ASTM test is more severe than the Borås test.

Comparing the results from the accelerated performance testing with the pore protection ratio determined and applying the tentatively suggested requirement

* Pore protection ration more than 0.25

it can be observed that three concretes apparently having sufficient pore protection ratio are rejected by the ASTM test, and two by the Borås test. The results indicate that the high pore protection ratio values measured on dense concretes may be due to insufficient initial capillary suction.

2.5 Conclusions on the Influence of Material Parameters on Frost Resistance

The frost damaged structures were found to be characterized by one or more of the following conditions:

* High internal moisture content
* No entrained air or very low content of entrained air
* Low pore protection ratio.

The present investigation confirms the traditionally used requirements to air void structure and air content needed to obtain freeze/thaw resistant concrete. Since a notable part of the investigated concrete has properties comparable to modern high performance concrete, the above results indicate that such concretes also need air entrainment to resist freeze/thaw action.

2.6 Reservations

The conclusions are based on several assumptions, some of which are not valid for all the concrete structures investigated:

* The damages contributing to the classification of the in situ performance of the structures are frost damages

* The in situ conditions of the structures have reached an equilibrium situation with respect to moisture content
* The concrete cores tested are representative for the concrete in the structures
* The exposure class chosen for each structure is representative for the actual local exposure
* The concrete material tested is comparable to modern, high performance concrete

3 Investigations

The aim of the investigations was to obtain possible correlation between in situ performance and laboratory frost testing, and to characterize concrete material properties. The investigation programme comprised two separate tasks - A and B - as outlined in Table 3.1.

Two hundred and four cores from 26 Danish concrete structures of varying age (1953-1985), composition, and visual appearance have been investigated by several methods in the search for possible correlation between frost testing results in the laboratory and the actual behaviour regarding frost attack of the concrete after several years in a more or less aggressive environment. Structures selected are bridges (decks, edge beams, barriers, columns, walls) and pavements, ref. Table 3.2. From each structure cores for testing have been drilled from a small area. Furthermore, the environmental exposure condition and surface orientation as well as the visual appearance of the concrete have been described.

3.1 Selection of Concrete Structures for Frost Testing (Task A)

Referring to field experience of research team and inspection protocols from the Bridge Division of the Danish Road Directorate, a number of bridges (decks, edge beams, safety barriers, columns, retaining walls) and pavements representing good as well as poor frost resistance properties were selected for further testing. Important parameters in the selection process were the visual appearance (signs of scaling or cracking), environmental conditions (moisture, salt spray, etc.), and the w/c-ratio. It was aimed at obtaining a number of older (approximately 10 to 40 years) structures of concrete with low w/c, with and without air-entrainment, and low capillary porosity comparable to modern high performance concrete.

In total 32 structures were selected as possibly suited for the purpose. The aim was to obtain approximately one third with severe damages, approximately one third with less severe damages, and the rest with no damages.

Table 3.1: Investigations (data are given in separate data reports).

Activity	No. of tests	Data report No.
Task A - Selection of structures		
Pointing out structures, data collection		1
Inspection and description of structures, marking out cores, photo documentation	26	1
Inspection and classification of environment	26	1
Task B - Laboratory Testing		
Detailed work plan, drilling and handling of cores etc.	-	2
Description and distribution of cores	204	3
Moisture tests and sorption characteristics (relative humidity, moisture content, degree of saturation, pore protection ratio)	26 x 2	4+5
Air void analysis	25	6
Thin section analysis, crack detection and macro analysis	25	7
Frost test, Borås	25	8
Frost test, modified Borås method	8	9
Frost test, modified ASTM 666, Procedure A	25	10
Analysis of tested samples (micro- and macrostructure)	8	11

All structures were inspected and described regarding concrete appearance as well as environmental conditions. Cores (eight per structure) were marked out by the inspection team in a small, representative area for each structure, to secure that each set of eight cores corresponds to "one" sample regarding concrete material characteristics and environmental conditions.

The outcome of the inspection and drilling operations was 25½ sets of 8 cores as unforseen difficulties (asphaltic layers, demolition, traffic hindrances etc.) impeded full implementation of the plan. These 204 cores in total were further treated and investigated as described in section 3.2 (task B of the programme).

Table 3.2: Concrete structures investigated

Sample No.	Location	Part	Built year
B1 V7	Ølby-Ringsted	Slab	1976
B2 V8	Ølby-Ringsted	Slab	1976
B3 V2	Ølby-Ringsted	Slab	1976
B4 D7	Traffic island	Deck	1964
B6 S5	B10-0050	Column	1971
B8 K12	Fiskebæk	Crash barrier	1981
B8 K6	Fiskebæk	Chrash barrier	1981
B9 D2	VD 106-6004	Deck (membrane)	1983
B10 D3	VD 515-1621	Deck	1969
B12 D3	Munkholm	Deck	1975
B13 D6	VD 515-0151	Deck (membrane)	1981
B15 BN1	DSB 14812	Bridge wall	1979
B15 BS1	DSB 14812	Bridge wall	1979
B16 S3	DSB 14832	Column	1975
B17 S8	DSB 14829	Column	1975
B18 S7	DSB 14808	Column	1974
B24 D1	M14-0050	Edge beam	1953
B25 S6	Mølleå, bridge	Column	1955
B26 V1	Borrevejle, bridge	Retention wall	1972
B27 G2	Farø	Crash barrier	1984
B28 V5	Kastrup, runway	Slab	1960
B29 V8	Sydmotorvejen	Slab	1985
B31 VN2	Glostrup, bridge	Retention wall	1975
B31 VS6	Glostrup, bridge	Retention wall	1975
B32 VN7	Brøndby, bridge	Retention wall	1980
B32 VS1	Brøndby, bridge	Retention wall	1980

3.2 Laboratory Testing (Task B)

After drilling of the cores (each 100 mm in diameter, and having a length of at least 200 mm, if possible) they were rapidly cleaned and immediately wrapped in thick, impervious plastic material when surface dry. The cores from the different structures were stored and treated as uniformly as possible before further testing.

Testing - ref. list in Table 3.1 - took place at different laboratories in such a way that all tests of the same kind, e.g. moisture tests, were performed at one laboratory using one core from each of the 25 structures, and e.g. thin section and macro analysis were performed at another laboratory using another core from the structure. The "half set" with 4 cores was investigated by moisture measurements and ASTM frost testing only.

3.2.1 Accelerated Frost Testing

Two frost testing methods have been selected according to the Supplementary Research [Geiker et al, 1996] to calibrate laboratory testing results with in situ performance. As was pointed out in the State of the Art Report [Laugesen et al., 1996] two different types of frost damage - surface scaling and internal cracking - are observed in practice, and to investigate each of these mechanisms two different methods are necessary. The selected methods are the Swedish Borås method (SS 13 72 44), Procedure III for surface scaling and the ASTM C 666, Procedure A (modified) for internal cracking.

For a smaller number (8) of the selected structures a modified version of the Borås test method - including a drying at 50°C before testing by the standard procedure - was applied in addition to the standard method. The modification of the conditioning was proposed based on investigations of cement paste showing that drying increases the amount of freezable water at unchanged moisture content, ref. [Geiker at al, 1996]. The modification of the ASTM method - type of measurement and length of specimen - is dealt with below.

From each structure three cores were tested by the modified ASTM C 666 method, Procedure A, at one laboratory, and three other cores were tested by the Borås method (normal procedure) at another laboratory. The modified Borås method was performed on extra slices from the same cores as used in the normal Borås method, and at the same laboratory.

3.2.1.1 Borås Method, SS 14 72 44, 1995 (III) Standard and Modified

Based on the supplementary research [Geiker et al, 1996] two series of surface scaling tests have been made on concrete cores taken from different concrete structures.

Standard Borås

Specimens from concrete cores from 25 structures have been tested according to the Swedish standard SS 13 72 44, 1995, the so-called Borås method, procedure III. Details on the testing are given in Appendix B. The method applied deviates from the SS 14 72 44 by the use of demineralized water in stead of tap water. The specimens were 50 mm slices sawed from 100 mm diameter cores.

Two slices were tested from each of 3 cores, except when also testing according to the modified Borås method was to take place. In this case one slice from each core was tested by each method.

Modified Borås

Specimens from cores from 8 structures selected among the 25 above mentioned have also been frost tested according to a modified Borås method. The specimens were 3 of the 6 sawed slices mentioned above.

The difference between these two methods is the conditioning before testing. In the modified Borås the specimens have been dried for 14 days in an oven at 50 °C at the corresponding relative humidity, followed by cooling down to room temperature and re-saturation for 14 days covered with water on the surface to be exposed. (In the standard Borås the specimens have been stored for 7 days in a room with temperature 20 °C and relative humidity 65 % RH followed by 3 days covered with water on the surface to be exposed.)

As a supplement to the measurement of surface scaling length change during freeze/thaw exposure was measured diagonally 10 mm and 25 mm from top of the exposed surface.

3.2.1.2 Modified ASTM C 666-92, Procedure A

The testing was carried out in agreement with the ASTM C 666-92, procedure A test method with 2 modifications:

Measure

The length change - optional according to ASTM C 666-A - as measure of the freeze/thaw damage has been applied instead of the normally prescribed determination of dynamic modulus of elasticity. The length change is by more researchers considered to be the more consistent measurement of the two, e.g. [Pigeon et al., 1996], [Laugesen et al, 1996].

Sample length

The samples tested were cores with a diameter of 100 mm and a cut length of 135-140 mm, taken from a core of minimum 200 mm length. This length is less than prescribed for cast samples. However, the general low spread in results from the same structure and the good correlation between visual damage and measured expansion (see below) indicate that the applied sample length is adequate for achieving a representative measure. It is, furthermore, estimated that the applied sample length is the maximum practically possible for many structures.

The description of the procedures applied at DBT for the HETEK project, is given in Appendix C. A new system for retaining the water around the samples was applied in the present project. This new system proved to be well functioning in relation to both handling the samples and securing removal of sources of error.

3.2.2 Testing of Selected Material Parameters

For the documentation of the representativity of the investigated concrete with regard to high performance concrete each concrete has been further analyzed regarding air void parameters, moisture conditions, sorption characteristics, pore protection ratio, w/c-ratio, homogeneity, presence of cracks, void-filling etc.

Furthermore, the order of priority of material parameters influencing the frost resistance of concrete structures and the results of laboratory frost testing has been evaluated.

3.2.2.1 Capillary Saturation and Pore Protection Ratio Testing

The pore protection ratio as defined by [Vuorinen, 1984] is the result of a testing expressing the active (effective) air pore volume in a capillary saturated material in relation to the total pore volume.

The testing includes the following steps:

- Capillary suction until constant weight (approximately 400 hours)
- Saturation under pressure, 15 MPa, for 24 hours
- Heating at 105°C to constant weight

The specimens tested were core slices of a thickness of approximately 20-30 mm (Vuorinen recommended Ø150 and length 300 mm specimens for concretes with w/c=0.5-0.6, ref. [Fagerlund, 1997]). Capillary saturation is assumed within the testing time. This has to be confirmed for lower w/c-ratios.

The degree of capillary saturation is calculated according to the equation:

$$S_{capp}=\frac{m_{in\ situ}-m_{105}}{m_{capp}-m_{105}}$$

where:

* $m_{in\ situ}$ is the sample weight as drilled
* m_{capp} is the sample weight at constant weight, after approximately 400 hours capillary saturation
* m_{105} is sample weight after drying at 105 °C

The pore protection ratio, P_r, is calculated according to the equation:

$$P_r=\frac{m_{press}-m_{capp}}{m_{press}-m_{105}}$$

where:

* m_{press} is the sample weight after 24 hours of water saturation in a pressure of 15 MPa

3.2.2.2 Petrographical Investigations

From each set of eight cores from each structure one core has been selected for petrographical investigations. The full core was first impregnated under vacuum with epoxy containing a fluorescent dye, and then cut in halves to reveal possible frost attack related presence of cracks and porosities, where intrusion of epoxy showed such defects.

Secondly, an epoxy impregnated thin section was prepared from the exposed surface to a depth of 45 mm. By use of a polarizing microscope with extension for fluorescense microscopy the microstructure was analysed, thereby obtaining information on w/c-ratio, homogeneity, cement type, presence of pozzolans, aggregate, microcracks and coarser cracks, air voids, air void filling, and possible signs of deterioration/frost damage at the exposed surface or deeper.

The information obtained from the petrographical analysis regarding frost attack is part of the overall evaluation of degree of damage, combined with input from the visual inspection.

3.2.2.3 Air Void Characterizations

Measurements of air void parameters have been performed on one core from each set of eight cores from each structure. The measurements have taken place in accordance with [ASTM C 457, 1982] by use of the linear traverse method. Results obtained have been recalculated from volume percent of concrete to volume percent of 'kitmasse' where 'kitmasse' represents the volume of concrete minus the volume of aggregate. 'Kitmasse' includes cement paste, pozzolans, admixtures, and air.

Throughout this report air void contents referred to are voids smaller than 0.35 mm, related to volume of 'kitmasse'. Air voids larger than 2 mm are not included in the calculations of spacing factor.

4 Results and Discussion

An overview of the test results is presented in Appendix A. Detailed results are found in the separate data reports. The results are listed without any sorting except for the order of inspection. The core designation represents the full set of eight (four) cores.

4.1 Classification of Exposure

Environmental exposure vary in aggressivity with regard to frost damage. For the present purpose of recommending acceptance criteria for concrete structures, three exposure classes were defined:

1: Structures exposed to frost and water, with or without salt
  - splash zone structures
  - pavements, slabs
  - edge beams
  - decks without membrane or with failing membranes
  - columns and vertical walls, continuously moisture exposed
  - back-filled support walls and retention walls without membranes

2: Structures exposed to frost and sometimes to water, with or without salt
  - decks with intact membranes
  - crash barriers
  - columns and vertical walls, not exposed to capillary suction, but less than 1.5 m from splash

3: Vertical surfaces exposed to frost, but rarely to water and not to salt
  - back-filled retention walls with membranes
  - sheltered columns

The above description of exposure classes should be harmonized with descriptions in the European standard, when available.

Based on the in situ inspection reports, exposure classes for the actual structural elements were selected, ref. Table 4.3.1, Section 4.3.

4.2 Concrete Characteristics

Selected materials data from present investigation are given in Table 4.5.1.1, Section 4.5.1. Eighteen of the 24 concrete structures investigated by thin section analysis have a measured low porosity (corresponding to w/c=0.35-0.45) in the range characterizing high performance concrete thereby being of special relevance to this project, ref Appendix A, microstructure. Regarding air entrainment, a rather low air content is found in most of the air entrained structures, and more than a third of the structures are not air entrained.

4.3 In Situ Performance

The degree of frost damage is not easily assessed by a visual inspection only. Internal damage, typically surface parallel cracks are often not visible from the outside, and surface scaling may not only be caused by frost but also be due to a weaker surface layer (wear on pavement surfaces). Frost damages have thus been evaluated involving visual inspection as well as micro- and macrostructural investigations.

The degree of frost damage of the investigated structures has been classified from 0 to 3, where 0 represents no damage and 3 a severely damaged structure with internal crack formation.

Results of the in situ evaluations, the petrographic investigations, and the combined characters of damage degrees are shown in Table 4.3.1. Furthermore, supplementary comments on the damage classification are given.

The result of this classification was that five structures are classified by 2-3 (some to much frost damaged) and 21 by 0-1 (no frost damage or slight surface scaling), ref. Table 4.3.2. The outcome is not quite as severe as expected from initial input from the Danish Road Directorate and experience of the research team.

Concrete structure					Condition rating			
Sample	Location	Part	exposure	build	in-situ.	petro.	total frost	Comments
no.			class	year	frost eval.	frost eval.	eval.	
B1 V7	Ølby-Ring.	slab	1	1976	1	1	1	
B2 V8	Ølby-Ring.	slab	1	1976	0	1	1	
B3 V2	Ølby-Ring.	slab	1	1976	1	1	1	
B4 D7	Traff.islnd	deck	1	1964	2	3	1	early frost damage at surface
B6 S5	B 10-0050	column	3	1971	1	0	1	
B8 K12	Fiskebæk	crash bar.	2	1981	1	0	1	spalling over coarse aggregate in nearby elements
B8 K6	Fiskebæk	crash bar.	2	1981	1	0	1	spalling over coarse aggregate in nearby elements
B9 D2	VD106-6004	deck,membran	2	1983	0	0	0	
B10 D3	VD515-1621	deck	1	1969	0	0	0	
B12 D3	Munkholm	deck	1	1975	2	1	2	cores taken in areas which do not reveal frost damage
B13 D6	VD515-0151	deck,membran	2	1981	0	0	0	
B15 BN1	DSB14812	bridge wall	1	1979	3	3	3	
B15 BS1	DSB14812	bridge wall	1	1979	3	3	3	
B16 S3	DSB14832	column	2	1975	1	0	1	
B17 S8	DSB14829	column	2	1975	1	0	1	
B18 S7	DSB14808	column	3	1974	1	2	1	surface cracking not due to frost
B24 D1	M14-0050	edge beam	1	1953	2	NA	2	
B25 S6	Mølleå,bridge	column	3	1955	0	0	0	
B26 V1	Borrevejle	retent.wall	1	1972	1	3	3	damaging ASR observed in petrographic analysis
B27 G2	Farø	crash bar.	2	1984	0	0	0	
B28 V5	Kastrup,rnw	slab	1	1960	0	1	1	based on earlier investigation, concrete is considered frost susceptible in exp.class 1
B29 V8	Sydmotorway	slab	1	1985	0	0	0	
B31 VN2	Glostrp,bridg.	retent.wall	1	1975	1	1	1	
B31 VS6	Glostrp,bridg.	retent.wall	1	1975	1	1	1	
B32 VN7	Brøndb,bridg	retent.wall	3	1980	1	1	1	
B32 VS1	Brøndb,bridg	retent.wall	3	1980	1	1	1	

Table 4.3.1: In-situ performance, classification of damage degree

Table 4.3.2 Distribution of the 26 investigated concrete structures according to frost damage and exposure classes.

Exposure class	No to little frost damage (damage degree 0-1)	Some to much frost damage (damage degree 2-3)
1	9	5
2	7	0
3	5	0

4.3.1 Problem Areas in the Damage Classification of Structures

The conditions of the structures are described as found in the summer of 1996. Presently undamaged structures may have large variations in potential for future freeze/thaw deterioration and may thus at a later stage be classified differently. A critical degree of saturation may be reached due to increasing moisture content or due to filling of air voids by ettringite and calcium hydroxide as frequently seen in moisture loaded concretes. Hence, part of the concrete structures now classified with regard to degree of frost damage as 0 and 1 (undamaged to little damage) may soon change to damage degree 2 or even 3 (some to much freeze/thaw damage), while other concrete structures may remain undamaged.

This should be born in mind, especially because the structures vary in age (from 15 to 43 years, summer 1996).

Thus, when comparing performance test results with the 1996-rating of the structures conditions, some of the points in the plot may be labile. One such example is structure B28, being a concrete pavement, 'Runway 12.30', known to be quite susceptible to freeze/thaw damage. Even small changes in moisture condition in situ - e.g. by marking small fields of the surface with paint - makes the surface markedly vulnerable to freeze/thaw [Henrichsen, 1997]. At the present 1996-rating, this concrete pavement was rated as 1 (little freeze/thaw damage).

The presence of harmful alkali silica reactions in some structures complicates the diagnosis of frost damages.

4.4 Evaluation of Methods for Accelerated Frost Testing

4.4.1 Evaluation of the Borås Method (III), Standard and Modified

4.4.1.1 Applied Test Methods

The standard and modified Borås methods applied are described in Section 3.2.

4.4.1.2 Test Results

The data are presented in the separate data reports, and summarized in Table 4.4.1.1. The modified Borås method appears to cause a significantly smaller amount of surface scaling of the actual concretes than the standard Borås method. It appears that the severely dried specimens do not take up enough moisture during re-saturation and testing to increase the frost susceptibility compared to specimens exposed to standard conditioning. This is in accordance with observations from tests conducted in the supplementary research [Geiker et al, 1996].

Three sets of specimens were taken from delaminated cores (B15BN, B15BS, and B26). The very large amount of surface scaling measured may be due to initial damage in the cores.

On the 3 x 8 specimens tested according to the modified Borås (II) method length changes between -0.11 % and +0.06 % (mean of 3) have been measured after 56 cycles (testing of B6 and B31 was stopped after 7 and 14 cycles, respectively, in order to be able to measure length changes).

4.4.1.3 Correlation between Standard Borås (III) Test Results and In situ Performance

In Table 4.4.1.2 and 4.4.1.3 the correlation between performance in the accelerated test and in situ is illustrated, in Table 4.4.1.3 the exposure conditions are also taking into account.

Concrete structure					Standard Borås								Modified Borås						Damage
Sample	Location	Part	expos.	build	m7	m14	m28	m42	m56	st.dev.	CV, %	m56/m28	m7	m14	m28	m42	m56	m56/m28	degree
no.			class	year	(kg/m2)	(kg/m2)	(kg/m2)	(kg/m2)	(kg/m2)	(m56)	(m56)		(kg/m2)	(kg/m2)	(kg/m2)	(kg/m2)	(kg/m2)		
B1 V7	Ølby-Ring.	slab	1	1976	0,06	0,08	0,11	0,17	0,2	0,11	56	1,7	0,02	0,03	0,04	0,08	0,1	2,3	**1**
B2 V8	Ølby-Ring.	slab	1	1976	0,15	0,36	1,24	2,30	3,5	4,63	134	2,8	0,01	0,02	0,04	0,07	0,1	3,3	**1**
B3 V2	Ølby-Ring.	slab	1	1976	0,22	0,60	0,15	2,32	3,5	5,41	156	2,9							**1**
B4 D7	Traff.islnd	deck	1	1964	0,12	0,21	0,70	1,30	2,0	1,33	67	2,9							**1**
B6 S5	B 10-0050	column	3	1971	1,13	0,82	5,06	14,99	-	*19,83*		>2	0,05	0,53	-	-	-	-	**1**
B8 K6	Fiskebæk	crash bar.	2	1981	0,01	0,01	0,10	0,07	1,1	1,65	144	11,8	0,02	0,02	0,02	0,02	0,0	1,3	**1**
B8 K12	Fiskebæk	crash bar.	2	1981	0,02	0,03	0,06	0,13	0,2	0,35	145	4,1							**1**
B9 D2	VD106-6004	deck,memb.	2	1983	0,04	0,06	0,09	0,11	0,4	0,74	189	4,4							**0**
B10 D3	VD515-1621	deck	1	1969	0,02	0,03	0,05	0,05	0,1	0,05	67	1,6							**0**
B12 D3	Munkholm	deck	1	1975	0,02	0,03	0,07	0,11	0,1	0,05	34	2,2	0,01	0,02	0,03	0,03	0,0	1,1	**2**
B13 D6	VD515-0151	deck,memb.	1	1981	0,04	0,07	0,15	0,22	0,3	0,46	140	2,2							**0**
B15 BN1	DSB14812	bridge wall	1	1979	5	10	-	-	-	*23,47*		-							**3**
B15 BS1	DSB14812	bridge wall	1	1979	2	7	27	-	-	*42,34*		-							**3**
B16 S3	DSB14832	column	2	1975	0,06	0,10	0,16	0,23	0,5	0,44	90	3							**1**
B17 S8	DSB14829	column	2	1975	0,03	0,03	0,04	0,05	0,1	0,02	40	1,5							**1**
B18 S7	DSB14808	column	3	1974	0,06	0,12	0,40	0,80	1,5	1,30	85	3,9							**1**
B24 D1	M14-0050	edge beam	1	1953	NA	NA	NA	NA	NA	NA		NA							**2**
B25 S6	Mølleå,bridge	column	3	1955	0,14	1,35	16,64	32,31	-	23,64		>2	0,01	0,07	0,25	0,26	0,8	2,5	**0**
B26 V1	Borrevejle	retent. wall	1	1972	3,59	12,53	58,60	-	-	*10,52*		-							**3**
B27 G2	Farø	crash bar.	2	1984	0,01	0,01	0,04	0,08	0,1	0,06	53	2,9							**0**
B28 V5	Kastrup,rnw	slab	1	1960	0,05	0,22	0,96	1,83	3,2	2,64	82	3,4							**1**
B29 V8	Sydmotorway	slab	1	1985	0,01	0,01	0,02	0,06	0,1	0,03	36	4							**0**
B31 VN2	Glostrp,bridg.	retent.wall	1	1975	0,09	0,47	3,72	16,88	-	*12,27*		>2	2,15	-	-	-	-	-	**1**
B31 VS6	Glostrp,bridg.	retent.wall	1	1975	0,14	0,47	1,51	3,24	5,2	*2,49*		3,5							**1**
B32 VN7	Brøndb,bridg	retent.wall	3	1980	0,04	0,01	0,02	0,03	0,0	0,01	41	1,8	0,02	0,04	0,04	0,08	0,1	3,1	**1**
B32 VS1	Brøndb,bridg	retent.wall	3	1980	0,05	0,28	1,62	7,54	8,9	*1,33*		5,5							**1**

Table 4.4.1.1: Test results, standard and modified Borås method (III)

Table 4.4.1.2 The 25 structural elements tested, arranged according to in situ performance versus amount of scaling after 56 cycles, m_{56} in kg/m^2. (* Initially damaged specimens)

	Number of structures			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	6	4	1	0
$0.5 \leq m_{56} < 1.0$	0	1	0	0
$m_{56} \geq 1.0$	2	6	2	(3)*

Table 4.4.1.3 The 25 structural elements tested, ordered according to exposure class and in situ performance versus amount of scaling after 56 cycles, m_{56} in kg/m^2. Structure nos. are given in brackets. (*Initially damaged specimens. NA: Not analyzed)

	Number of structures, **exposure class 1**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	3 (B10, B27, B29)	1 (B1)	1 (B12)	0
$0.5 \leq m_{56} < 1.0$	0	0	0	0
$m_{56} \geq 1.0$	1 (B4)	3 (B2, B3, B28)	1 (B31VS)	3 (B15BS, B15BN, B26) *
$m_{56}/m_{28} < 2$	1 (B10)	1 (B1)	0	NA
	Number of structures, **exposure class 2**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	3 (B9, B13, B27)	2 (B8K12, B17)	NA	NA
$0.5 \leq m_{56} < 1.0$	0	1 (B16)	NA	NA
$m_{56} \geq 1.0$	0	1 (B8K6)	NA	NA
$m_{56}/m_{28} < 2$	0	1 (B17)	NA	NA
	Number of structures, **exposure class 3**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	0	1 (B32VN)	NA	NA
$0.5 \leq m_{56} < 1.0$	0	0	NA	NA
$m_{56} \geq 1.0$	1 (B25)	3 (B6, B18, B32VS)	NA	NA
$m_{56}/m_{28} < 2$	0	1 (B32VN)	NA	NA

Assuming a requirement to maximum scaling after 56 cycles of 0.5 kg/m^2 (or 1.0 kg/m^2), one concrete giving rise to low in situ performance (damage degrees 2 or 3) passes the test, B12 (m_{56}=0.1 kg/m^2), ref. Table 4.4.1.3. B12 is the Munkholm bridge deck from 1975 which is in exposure class 1. It may be that the concrete cores taken do not represent the damaged concrete, as the petrographic evaluation resulted in a damage classification 1, ref. Table 4.3.1.

Concrete from structures clearly judged as damaged (degree 3) show surface scaling in excess of 1 kg/m^2 ($m_{56} \geq 1.0$), ref. Table 4.4.1.3.

Application of the requirement $m_{56}<0.5$ will cause rejection of 4, 1 and 5 concretes presently characterized with damage degree 0-1 in the exposure classes 1, 2, and 3, respectively; and application of the requirement $m_{56}<1.0$ will cause rejection of 4, 1, and 4 concretes with damage degree 0-1 in the exposure classes 1, 2, and 3, respectively, ref. Table 4.4.1.3. The reason for this may be that damages are to come due to a possible critical moisture state not having been reached yet, ref. Section 4.3, or that the test method is more severe than the in situ exposure for these structures. Concerning the latter, the accepted probability of rejecting concrete with proper in situ performance should be selected by the owner. Reference is given to Section 4.5, discussing the effect of material parameters on frost resistance.

Concerning the so-called acceleration factor (m_{56}/m_{28}) only 2 of the 4 concretes in exposure class 1 showing $m_{56}<0.5$ kg/m^2 and having damage degree 0-1 meet the requirement of $m_{56}/m_{28} \leq 2$.

Based on the above, the following requirement to specimens from drilled cores tested according to the standard Borås method could be argued relevant:

Exposure class 1: $m_{56} < 0.5$ kg/m^2

The results indicate that the requirement for exposure class 1 might be increased to 1 kg/m^2. However, this should be further documented. The Swedish Road Directorates recommendation of $m_{56}<1.0$ kg/m^2 for drilled cores is based on experience which do not cover all the types of powder compositions presently used in Denmark.

Furthermore, the assumed low possibility of accepting concrete with low freeze/thaw resistance when omitting requirements to the so-called acceleration factor, $m_{58}/m_{28}<2$ should be further documented.

Two few data on damaged structures (damage degree 2-3) are available for concluding regarding requirements for concrete structures in exposure classes 2 and 3. However, based on an evaluation of the possible exposure we tentatively suggest the following requirement applied for drilled cores:

Exposure class 2: $m_{56} < 1.0$ kg/m

In order to reduce the duration of testing it could be considered to include a criterion for maximum scaling after say 28 days. The present - and limited - results for the concrete which pass the standard Borås method indicate a safe estimate of the scaling after 56 cycles to be 5 times the result after 28 cycles, ref Table 4.4.1.2. Thus, the requirements could be: Exposure class 1: $m_{28} < 0.1$ kg/m^2 and exposure class 2: $m_{28} < 0.2$ kg/m. Before applying these requirements, all available data on standard frost testing of high performance concrete should be evaluated. One other possibility of limiting the duration of testing would be to decrease the duration of each freeze/thaw cycle, say from 24 to 12 hours, ref. [Fagerlund, 1997]. The effect of this has not been included in the present investigation.

4.4.1.4 Correlation Between the Modified Borås (III) Test Results and In situ Performance

In Table 4.4.1.4 and 4.4.1.5 the correlation between performance in the accelerated test and in situ is illustrated, in Table 4.4.1.5 also taking into account the exposure conditions.

The modified Borås method has only been applied to one set of specimens from a structure with damage degree 2 (B12) and none of degree 3. As mentioned above, the in situ performance of this structural concrete may be classified too high, ref. Section 4.3. Thus, at present we can not conclude regarding the applicability of the modified Borås for frost testing of high performance concrete.

Application of the requirement $m_{56}<0.5$ will cause rejection of 1 of 3, 0 of 1 and 2 of 3 concretes presently characterized with damage degree 0-1 in the exposure classes 1, 2, and 3, respectively; and application of the requirement $m_{56}<1.0$ will cause rejection of 1 of 3, 0 of 1, and 1 of 3 concretes with damage degree 0-1 in the exposure classes 1, 2, and 3, respectively, ref. Table 4.4.1.3. The reason for this may be that damages are to come due to a critical moisture state that has not been reached yet in situ, ref. Section 4.3, or that the test method is more severe than the in situ exposure for these structures. Concerning the latter, the accepted probability of rejecting concrete with proper in situ performance should be selected by the owner.

Table 4.4.1.4 The 8 structural elements tested by the modified Borås method, ordered according to in situ condition ('grade') versus amount of scaling after 56 cycles, m_{56} in kg/m^2. NA: Not analyzed.

	Number of structures			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	0	4	1	NA
$0.5 \leq m_{56} < 1.0$	1	0	0	NA
$m_{56} \geq 1.0$	0	2	0	NA

Table 4.4.1.5 The 8 structural elements tested according to the modified Borås method, ordered according to exposure class and in situ condition ('grade') versus amount of scaling after 56 cycles, m_{56} in kg/m^2. Structure nos. are given in brackets. NA: Not analyzed.

	Number of structures, **exposure class 1**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	NA	2 (B1, B2)	1 (B12)	NA
$0.5 \leq m_{56} < 1.0$	NA	0	0	NA
$m_{56} \geq 1.0$	NA	1 (B31N)	0	NA
	Number of structures, **exposure class 2**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	NA	1 (B8K6)	NA	NA
$0.5 \leq m_{56} < 1.0$	NA	0	NA	NA
$m_{56} \geq 1.0$	NA	0	NA	NA
	Number of structures, **exposure class 3**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$m_{56} < 0.5$	0	1 (B32VN)	NA	NA
$0.5 \leq m_{56} < 1.0$	1 (B25)	0	NA	NA
$m_{56} \geq 1.0$	0	1 (B6)	NA	NA

Based on the limited data available, the modified Borås method seems to cause less scaling than the standard Borås method and not to provide sufficient differentiation between different concrete qualities.

4.4.2 Evaluation of the ASTM C 666 Method

4.4.2.1 Applied Test Method

The method applied is described in Section 3.2.

4.4.2.2 Test Results

The expansion measured in the samples tested from the various structures range from negligible to very large, indeed exceeding the fracture strain, ref. Table 4.4.2.1:

- Small expansion, e.g. sample B3V7 showing a length change of 0.019 mm corresponding to an expansion of 0.014 % after 300 freeze/thaw cycles
- Large expansion, e.g. in structure B16 exceeding an expansion of 1 % after 36 freeze/thaw cycles.

Expansion in excess of 0.1% is accompanied by visible crack formation and disintegration. Based on these observations - and in spite of 0.1% being eight times the strain capacity - it is evaluated that 0.1 % expansion is an applicable limit distinguishing between deleterious and non-deleterious expansion. Thus, it could be suggested that 0.1 % expansion be used as an acceptance limit, not to be exceeded after a given number of cycles. The required number of cycles might presumably be dependent on exposure classes and service life time expectations.

Generally, the three samples within a test series showed similar expansion histories. Also the developments in damages such as pop-outs and crack formation appeared to be similar in most of the test series.

Concrete structure					Frost/Thaw (ASTM C666)-mod.							Pore
Sample	**Location**	**Part**	**exposure**	**build year**	**36 cycles**	**72 cycles**	**108 cycles**	**144 cycles**	**180 cycles**	**300 cycles**	**Remarks**	**protec.**
no.			**class**		**exp. (%)**	**exp. (%)**	**exp. (%)**	**exp. (%)**	**exp. (%)**	**exp. (%)**		**ratio**
B1 V7	Ølby-Ring.	slab	1	1976	0.01	0.01	0.04	0.07	> 0.10	> 0.30	failed cycl.betw.144-252	0.31
B2 V8	Ølby-Ring.	slab	1	1976	0.01	0.04	0.06	0.08	> 0.10	> 0.10	2 of 3 sampl. failed	0.34
B3 V2	Ølby-Ring.	slab	1	1976	0.03	0.04	0.06	0.07	0.09	> 0.10	1 of 3 sampl. failed	0.20
B4 D7	Traff.islnd	deck	1	1964	0,00	0,00	0.01	0.02	0.02	0.03		0.30
B6 S5	B 10-0050	column	3	1971	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10		0.09
B8 K12	Fiskebæk	crash bar.	2	1981	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10		0.17
B8 K6	Fiskebæk	crash bar.	2	1981	0,00	0.01	0.03	0.07	0.14	> 0.14		0.10
B9 D2	VD106-6004	deck,memb.	2	1983	0.02	0.1	0.18	0.19	> 0.20	> 0.20		0.43
B10 D3	VD515-1621	deck	1	1969	0.00	0.00	0.00	0.00	0.00	0.02		0.25
B12 D3	Munkholm	deck	1	1975	0.17	0.32	> 0.34	> 0.35	> 0.35	> 0.37	failed cycl.betw. 36-288	0.22
B13 D6	VD515-0151	deck,memb.	2	1981	0.00	0.02	0.03	0.14	0.04	0.05		0.22
B15 BN1	DSB14812	bridge wall	1	1979	not tested due to many cracks in cores							0.04
B15 BS1	DSB14812	bridge wall	1	1979	not tested due to many cracks in cores							0.04
B16 S3	DSB14832	column	2	1975	1.33	> 1.33	> 1.33	> 1.33	> 1.33	> 1.33		0.13
B17 S8	DSB14829	column	2	1975	0.14	0.40	> 0.40	> 0.40	> 0.40	> 0.40		0.16
B18 S7	DSB14808	column	3	1974	0.06	0.14	0.22	> 0.22	> 0.22	> 0.22		0.16
B24 D1	M14-0050	edge beam	1	1953	0.07	0.28	> 0.28	> 0.28	> 0.28	> 0.28		0.07
B25 S6	Mølleå,bridg	column	3	1955	1.05	> 1.05	> 1.05	> 1.05	> 1.05	> 1.05		0.13
B26 V1	Borrevejle	retent.wall	1	1972	not tested due to many cracks in cores							0.07
B27 G2	Farø	crash bar.	2	1984	0.00	0.01	0,00	0,00	0,00	0,00		0.18
B28 V5	Kastrup,rnw	slab	1	1960	0.00	0.02	0.06	0.11	> 0.15	> 0.15		0.14
B29 V8	Farø	slab	1	1985	0.00	0.02	0.13	0.25	> 0.25	> 0.25		0.15
B31 VN2	Glostrp,bridg.	retent.wall	1	1975	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10		0.13
B31 VS6	Glostrp,bridg.	retent.wall	1	1975	0.35	> 0.35	> 0.35	> 0.35	> 0.35	> 0.35		0.11
B32 VN7	Brøndb,bridg	retent.wall	3	1980	0.22	> 0.22	> 0.22	> 0.22	> 0.22	> 0.22		0.21
B32 VS1	Brøndb,bridg	retent.wall	3	1980	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10	>> 0.10		0.22

Table 4.4.2.1: Test results, Modified ASTM C 666 and pore protection ratio

The observed damage patterns accompanying the length changes measured, comprise:

- Formation of fine cracks perpendicular to the core length - sometimes formed mainly at a core-end 'shooting off the top'
- Expanding and scaling paste, causing exposure of coarse and fine aggregate (this corresponds to the formation of 'ring-cracks' as seen in freeze/thaw (test) damaged concrete and in concrete with distress caused by delayed ettringite formation [Johansen et al, 1994]
- Pop-outs at porous or alkali reactive coarse flint aggregate and porous palaeozoic coarse limestone aggregate
- Pop-outs at large bodies of entrapped air - this has not been recorded at laboratory testing before and should be further investigated (similar frost damages have been observed on concrete slabs [Henrichsen, 1997-b]
- Damages related to casting joints present in the tested cores (e.g. core B12D2). It could be suggested that expansion caused by damages of this type only, should not reject the concrete, even when expansion exceed the limit of 0.1 %, ref. also section on Parameters of Possible Influence on the Modified ASTM C 666 Test Results.

4.4.2.3 Parameters of Possible Influence on the Modified ASTM Test Results

The present work on modified ASTM C 666-A testing was associated with thorough visual inspection of the samples during testing. The results of these observations are presented below in a context of possible influence on the results of the measured expansions. Hence, this presentation can be regarded as an input to possible modifications of the test method, at least for testing in situ.

Reinforcement bars in the cored samples

Several of the tested structures revealed rebars when cored. This was the case for e.g. structures B8, B9 and B10. No frost deterioration was observed to occur in association with the rebar during testing. The exposed surface of the rebars all showed signs of rust formation during the testing.

It is concluded that the presence of rebars in cores for modified ASTM C 666-A testing does not influence the test results.

Casting joints

Several of the structures cored contained casting joints. During the modified ASTM C 666-A testing, the general indication was, that these joints caused deterioration exceeding that in the remaining part of the core. Hence, in e.g. specimens from structure B12 a deleterious expansion could be seen to develop at the casting joint.

It is concluded that samples for modified ASTM C 666-A testing, cores from in situ structures should not contain casting joints.

Moisture condition

The moisture condition of in situ structures may influence the results of the freeze/thaw testing. The moisture condition is regarded as representing a significant part of the materials parameters of the given structure, accordingly, the moisture condition of samples taken from in situ structures should not be changed before testing.

The conditioning of samples should be concentrated on securing the samples against any drying out, e.g. during the mounting of gauge studs, and before immersion in water when freeze/thaw testing can begin.

Entrapped air

For a few of the structures, the samples showed large pop-outs of concrete pieces placed over larger bodies of entrapped air. In several cases these pop-outs appeared to be related to a subsequent formation of fine cracks in the samples.

Hence, it is estimated that this feature have influence on the test results. However, it is unknown if this has a general relation to deterioration of in situ concrete.

Alkali Silica Reactions

When testing frost resistance of older structures, an influence of ongoing alkali silica reaction may be expected. This was seen in e.g. structure B17 showing low frost resistance: alkali silica reactions was seen causing abundant pop-outs on the exposed surfaces of the 3 tested samples.

It is not known, however, if the ongoing alkali reactivity observed in part of the structures have influenced the expansion measured during the freeze/thaw testing. Preferably, the samples should be without ongoing alkali silica reactivity.

4.4.2.4 Correlation Between Modified ASTM C 666, Procedure A, Testing and the In Situ Performance of the Structure

In Table 4.4.2.2 and Table 4.4.2.3, the results of the modified ASTM C 666-A freeze/thaw testing compared with the actual condition of the structures. In Table 4.4.2.3 also the exposure class is taken into account.

Exposure class 1

It is observed that both concretes with poor in situ performance (damage degree 2-3) show deleterious expansion within 108 freeze/thaw cycles.

On the other hand, the concrete in several presently well performing structures show poor freeze/thaw durability in the test, ref. Table 4.2.2.3. The reason for this may be that damages may come later when a critical moisture state having been reached in situ, ref. Section 4.3, or that the test method is more severe than the in situ exposure for these structures. Concerning the latter, the probability of rejecting concrete with proper in situ performance should be selected by the owner. Reference is given to Section 4.5, discussing the effect of material parameters on frost resistance.

Possible explanations for some of the discrepancies found between in situ performance and modified ASTM C 666-A testing are given below:

* Structure B1, Ølby-Ringstedmotorvejen, has damage degree 1. At the freeze/thaw testing, the expansions measured exceeded 0.1 % after 144 cycles (sample no. B1V2), and after 252 freeze/thaw cycles respectively (the remaining 2 samples). These results indicate a variation in the quality of the samples tested.

Observations made during the freeze/thaw testing confirmed the presence of alkali silica reactivity, causing some pop-outs. This may be a further cause of the discrepancies in performance of this structure. The concrete failed in the Borås testing.

* Structure B2, at another location at Ølby-Ringstedmotorvejen, has damage degree 1, yet the freeze/thaw testing gave deleterious expansion (> 0.1 %) after 72 freeze/thaw cycles for two of the samples. The remaining 1 sample showed close to nil expansion after 300 freeze/thaw cycles, i.e. it was unaffected by the freeze/thaw testing. These data indicate a marked variation in concrete quality or condition of the samples. It should be noted that the Borås testing of this structure also gave a high scaling value of 3.5 kg/m^3.

Table 4.4.2.2 The 23 structures tested, ordered according to in situ performance versus the ASTM C 666-A (modified) test results. (NA: Not analyzed)

Cycles to fail, c (exp. > 0.1 %)	Number of structures			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
c > 300	3	1	0	NA
180 < c ≤ 300	0	1	0	NA
108 < c ≤ 180	0	4	0	NA
c ≤ 108	3	9	2	NA

Table 4.4.2.3 The 23 structures tested, ordered according to in situ performance and exposure class versus ASTM C 666-A (modified) test results. (* Cores too cracked to be tested. NA: Not analyzed)

Cycles to fail, c (exp. > 0.1 %)	Number of structures, **exposure class 1**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3*
> 300	1 (B10)	1 (B4)	0	NA
180 < c ≤ 300	0	1 (B3)	0	NA
108 < c ≤ 180	0	3 (B1, B2, B28)	0	NA
c ≤ 108	1 (B29)	2 (B31VN, B31VS)	2 (B12, B24)	NA
Cycles to fail, c (exp. > 0.1 %)	Number of structures, **exposure class 2**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
c > 300	2 (B13, B27)	0	NA	NA
180 < c ≤ 300	0	0	NA	NA
108 < c ≤ 180	0	1 (B8K6)	NA	NA
c ≤ 108	1 (B9)	3 (B8K12, B16, B17)	NA	NA
Cycles to fail, c (exp. > 0.1 %)	Number of structures, **exposure class 3**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
> 300	0	0	NA	NA
180 < c ≤ 300	0	0	NA	NA
108 < c ≤ 180	0	0	NA	NA
c ≤ 108	1 (B25)	4 (B6, B18, B32VN, B32VS)	NA	NA

- Structure B28, runway in Kastrup, may be regarded as frost susceptible, ref. Section 4.3.

- Structure B29, Sydmotorvejen, has damage degree 0. As previously described this structure has hitherto been regarded as frost resistant, based on investigations both in situ and in the laboratory. The present freeze/thaw testing revealed deleterious expansions after 108 freeze/thaw cycles. Nothing in the available data reveals a cause for this response.

It is evaluated that the modified ASTM C 666-A test method is relevant for the testing of the frost resistance of concrete structures in exposure class 1 applying the following requirement to drilled cores:

Exposure class 1: Expansion after 300 freeze/thaw cycles < 0.1%

Further research is needed to unveil the present frost resistance of some of the structures, e.g. B2, 'Ølby-Ringstedmotorvejen', structure B28, and structure B29, 'Sydmotorvejen'.

Exposure class 2 and 3

Seven and five structures fall in exposure class 2 and 3, respectively, and none of them exhibit damages to a degree 2 or 3. Only two of the 12 concretes show less than 0.1 expansion after 300 freeze/thaw cycles in the modified ASTM C 666-A test. Eight of the 12 concretes showed complete failure in the modified ASTM C 666-A testing.

Based on the present scarce results, it is evaluated that neither the frost resistance of exposure class 2 and exposure class 3 structures are well described by the modified ASTM C 666-A test. However, the present data are too limited to draw any firm conclusions.

4.4.3 Evaluation of the Pore Protection Ratio

4.4.3.1 Applied Test Method

The method applied is described in Section 3.2.

4.4.3.2 Test Results

The data are given in Table 4.4.2.1. In the following, the in situ condition of the 26 structures are correlated to the results of the pore protection ratios measured, ref. Table 4.4.3.1.

Exposure Class 1

No concretes in exposure class 1 with low in situ performance (damage degree 2-3) have a pore protection ratio above 0.25. On the other hand only three of nine structures with acceptable in situ performance (damage degree 0-1) have a pore protection ratio above 0.25, ref. Table 4.4.3.1.

The critical pore protection ratio depends on the w/c-ratio of the concrete and the exposure conditions (+/- salt) [Fagerlund, 1997].

Although, there appears to be a large probability of rejecting a proper concrete we tentatively suggest the following requirement for the pore protection ratio in cores drilled from concrete structures in exposure class 1:

Pore protection ratio > 0.25

Further research is needed to confirm this, especially for low w/c-ratio concrete.

The testing of pore protection ratio is recommended used as a supplementary test for assessment of the probability of frost damage in situ.

Exposure Classes 2 and 3

Seven and five structures fall in exposure class 2 and 3, respectively, and none of them exhibit damages to a degree 2 or 3. Only one of the 12 concretes has a pore protection ratio above 0.25.

Based on the present scarce results, it is evaluated that the frost resistance of exposure class 2 or exposure class 3 structures are not well described by the pore protection ratio. However, the present data are too limited to draw any firm conclusions.

Table 4.4.3.1 The 26 structures tested, arranged according to in situ performance and exposure class versus pore protection ratio, P_r.

P_r	Number of structures, **exposure class 1**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$P_r > 0.30$	0	2 (B1, B2)	0	0
$0.25 < P_r \leq 0.30$	0	1 (B4)	0	0
$0.20 < P_r \leq 0.25$	1 (B10)	1 (B3)	1 (B12)	0
$0.10 < P_r \leq 0.20$	1 (B29)	3 (B28, B31VN, B31VS)	0	0
$P_r \leq 0.10$	0	0	1 (B24)	3 (B15BS, B15BN, B26)

P_r	Number of structures, **exposure class 2**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$P_r > 0.30$	1 (B9)	0	NA	NA
$0.25 < P_r \leq 0.30$	0	0	NA	NA
$0.20 < P_r \leq 0.25$	1 (B13)	0	NA	NA
$0.10 < P_r \leq 0.20$	1 (B27)	4 (B8K12, B8K6, B16, B17)	NA	NA
$P_r \leq 0.10$	0	0	NA	NA

P_r	Number of structures, **exposure class 3**			
	Damage degree 0	Damage degree 1	Damage degree 2	Damage degree 3
$P_r > 0.30$	0	0	NA	NA
$0.25 < P_r \leq 0.30$	0	0	NA	NA
$0.20 < P_r \leq 0.25$	0	2 (B32VN, B32VS)	NA	NA
$0.10 < P_r \leq 0.20$	1 (B25)	1 (B18)	NA	NA
$P_r \leq 0.10$	0	1 (B6)	NA	NA

4.4.4 Correlation between the Standard Borås, Modified ASTM C 666-A, and the Pore Protection Ratio

With the application of the suggested requirements to frost resistance of drilled cores from concrete structures in exposure class 1:

* ASTM C 666-A (modified): Less than 0.1% expansion after 300 cycles
* Borås (III): Less than 0.5 kg/m^2 after 56 freeze/thaw cycles

it appears that the ASTM test is more severe than the Borås test, ref. Figure 4.4.4.1 (log scale). Only the concrete, B4, is rejected in the Borås test but accepted in the ASTM test. By petrographical examination it was found that B4 has been subjected to frost in situ at a very early stage, thus some of the specimens tested may be initially damaged. On the other hand, seven concretes are rejected by the ASTM test, but not by the Borås test.

Comparing the results from the accelerated performance testing with the pore protection ratio determined and applying the tentatively suggested requirement

* Pore protection ratio > 0.25

it can be observed that three concretes apparently having sufficient pore protection ratio are rejected by the ASTM test, ref. Figure 4.4.4.1 (log versus linear scale). In the Borås test two concretes apparently having a sufficient pore protection ratio are rejected, ref. Figure 4.4.4.1 (log versus linear scale).

The concretes in question are ASTM: B1, B2, and B9, and Borås: B2 and B4. Except for B4, the concretes all have low w/c-ratio (0.35-0.38) and more water than corresponding to the air void content is being pressed into the specimens during pressure saturation after capillary suction, ref. Section 3.2.2. This indicates that the high pore protection ratio values measured on these dense concretes may be due to insufficient initial capillary suction.

4.5 The Effect of selected Material Properties on Frost Resistance

4.5.1 Introduction

Selected material properties are in this Section compared to results of the accelerated frost testing. Detailed data are given in the separate data report. The results of air void analyses, petrographical analyses, moisture testing, accelerated frost testing (standard

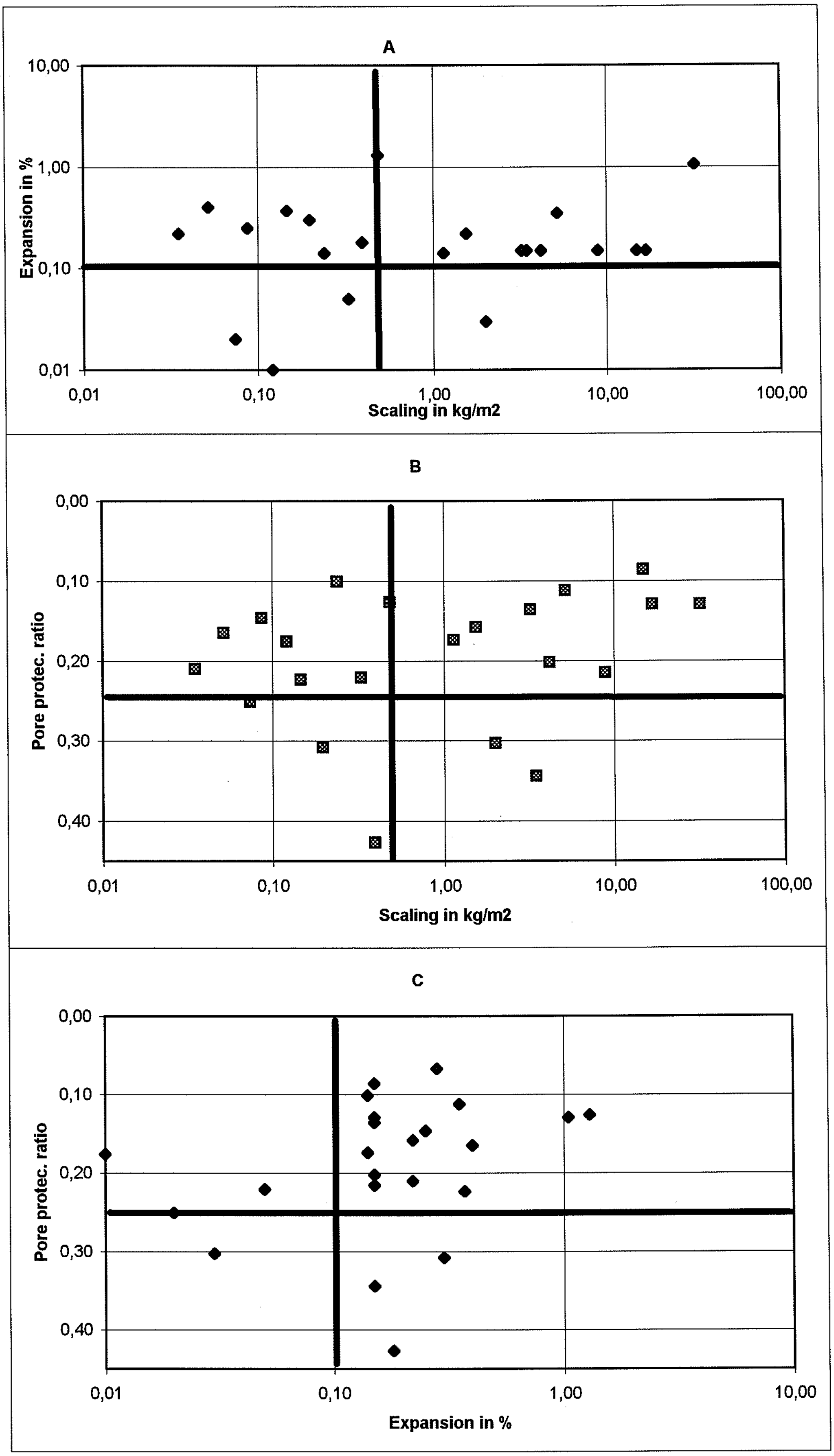

Figure 4.4.4.1: A: Surface scaling (Borås (III) method) versus expansion after 300 cycles (ASTM C 666-A, modified). B: Surface scaling after 56 cycles versus pore protection ratio. C: Expansion versus pore protection ratio.

Borås test (SS 13 72 44) and the modified ASTM C 666-A test), and the in situ investigations are summarized in Appendix A, and selected data on air void structure, microstructure and moisture content are given in Table 4.5.1.1.

A close relationship is observed between 'kitmasse' air [1] (<0.35 mm) and spacing factor, ref. Figure 4.5.1.1. The concretes fall in three main groups with regard to air content: below 4%, 6-8%, and above 10%. The first group represents generally non-air entrained concrete. The close relationship between 'kitmasse' air (<0.35 mm) and the spacing factor indicates that the spacing factor is a suitable parameter for the description of the air void distribution for air entrained concrete.

The results from the accelerated frost testing are dealt with in section 4.4.1 and 4.4.2.

4.5.2 Standard Borås Testing Method

The correlation between amount of 'kitmasse' air (<0.35mm) and the amount of scaling (kg/m2) after 56 cycles in the standard Borås method is illustrated in Figure 4.5.2.1.

The concretes with a higher total air content have been found to have an increased frost resistance according to the Borås method. The concretes with a 'kitmasse' air (<0.35mm) content above 8% are all frost resistant according to the recommended requirement for exposure class 1, i.e. surface scaling less than 0.5 kg/m^2 after 56 cycles, ref. Section 4.4.1.

According to Figure 4.5.1.1 minimum 8% air (<0.35mm) corresponds to a spacing factor of maximum 0.20 mm.

Between 6-8% 'kitmasse air' (<0.35mm) two of six concretes show more than 0.5 kg/m^2 surface scaling: B4, which has been exposed to early frost, and B8K6, which has a single specimen with a high scaling value of 3 kg/m^2 (approx. 15 times higher than the other specimens from the same sample).

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[1] 'Kitmasse' is understood as volume of cement paste (including pozzolans) and air voids

Concrete structure				Air void structure *					Moisture **						Microstructure						
Sample	Location	Part	build	total air	<2mm	<0.35mm	s.f.	s.surf.	RH (i)	RH (s)	Scap (i)	Scap (s)	U (i)	U (s)	w/c-ratio	inhom.	cracks	ettringite	moist.	air	remarks
no.			year	(%)	(%)	(%)	(mm)	(mm-1)	(%)	(%)			(%)	(%)	(mean)	(w/c-var.)	(>0.01)	filling	eval.	subj.	
B1 V7	Ølby-Ring.	slab	1976	7,5	5,7	2,4	0,38	20	94	93	0,95	0,89	4,9	4,4	0,35	high	few	high	2	3	
B2 V8	Ølby-Ring.	slab	1976	3,7	3,7	2,7	0,26	38	94	89	0,94	0,82	5,0	3,7	0,38	high	few	low	1	2	
B3 V2	Ølby-Ring.	slab	1976	10,0	7,6	1,7	0,67	10	93	85	0,95	0,87	4,5	3,9	0,35	high	few	high	2	2	
B4 D7	Traff.islnd	deck	1964	26,0	20,0	7,4	0,20	19	94	94	0,94	0,93	6,6	6,4	0,55	low	many	low	2	2	early frost
B6 S5	B 10-0050	column	1971	1,4	1,4	1,1	0,25	59	77	79	0,85	0,83	3,8	3,4	0,38	high	few	low	2	2	
B8 K6	Fiskebæk	crash bar.	1981	9,4	9,1	7,1	0,16	39	78	81	0,94	0,77	4,8	3,9	0,50	low	few	low	0	1	
B8 K12	Fiskebæk	crash bar.	1981	9,7	9,8	6,7	0,19	33	98	97	0,94	0,94	6,4	7,9	0,53	low	few	low	1	2	
B9 D2	VD106-6004	deck,memb.	1983	12,0	9,5	6,7	0,19	32	77	79	0,85	0,72	3,4	3,2	0,38	low	few	low	0	2	
B10 D3	VD515-1621	deck	1969	22,0	17,6	13,0	0,15	30	74	64	0,84	0,78	4,0	4,0	0,38	low	few	low	0	1	
B12 D3	Munkholm	deck	1975	5,6	5,3	3,1	0,33	24	73	74	0,85	0,71	3,7	2,4	0,35	high	few	high	2	2	ettr. 0-5mm
B13 D6	VD515-0151	deck,memb.	1981	19,0	18,6	11,0	0,20	22	78	79	0,88	0,79	3,0	3,2	0,38	high	few	low	1	1	
B15 BN1	DSB14812	bridge wall	1979	3,9	3,6	3,2	0,24	39	95	96	0,98	0,97	6,3	7,3	0,60	low	many	high	3	3	frost
B15 BS1	DSB14812	bridge wall	1979	2,3	2,3	1,3	0,34	33	99	97	0,99	1,00	6,2	7,8	0,60	high	many	high	3	3	frost
B16 S3	DSB14832	column	1975	7,3	6,0	3,0	0,25	30	83	75	0,84	0,76	5,4	4,8	0,38	high	few	low	1	2	
B17 S8	DSB14829	column	1975	6,9	6,7	3,8	0,21	36	85	82	0,85	0,74	5,4	4,6	0,43	low	few	low	1	2	
B18 S7	DSB14808	column	1974	5,2	4,3	3,5	0,18	48	80	83	0,82	0,74	5,1	3,7	0,45	high	many	low	1	2	frost ?
B24 D1	M14-0050	edge beam	1953	*NA*	*NA*	*NA*	*NA*	*NA*	90	96	0,98	0,96	6,4	4,7	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	
B25 S6	Mølleå,bridge	column	1955	4,4	3,3	1,0	0,66	15	76	64	0,82	0,75	3,7	3,3	0,38	high	few	low	1	3	
B26 V1	Borrevejle	retent. wall	1972	2,8	2,6	1,4	0,40	29	97	82	0,98	0,78	8,2	4,5	0,45	high	many	high	2	3	frost+ASR
B27 G2	Farø	crash bar.	1984	12,0	10,5	6,3	0,18	32	79	64	0,89	0,81	4,5	3,5	0,33	low	few	low	0	0	
B28 V5	Kastrup,rnw	slab	1960	14,0	10,7	1,9	0,44	13	92	88	0,91	0,82	5,4	5,8	0,43	high	few	low	1	3	
B29 V8	Farø	slab	1985	14,0	14,3	13,0	0,11	46	84	70	0,93	0,67	3,8	3,0	0,38	high	few	low	1	0	
B31 VN2	Glostrp,bridg.	retent.wall	1975	5,0	4,8	1,3	0,52	16	95	87	0,8	0,68	5,8	4,7	0,43	high	few	low	1	3	
B31 VS6	Glostrp,bridg.	retent.wall	1975	8,5	6,2	2,8	0,37	20	95	89	0,9	0,7	7,3	4,6	0,48	high	few	high	2	3	
B32 VN7	Brøndb,bridg	retent.wall	1980	11,0	9,4	6,3	0,18	34	87	82	0,83	0,71	4,2	3,5	0,40	high	few	low	1	1	
B32 VS1	Brøndb,bridg	retent.wall	1980	5,6	3,4	1,4	0,51	19	85	80	0,87	0,7	4,5	3,5	0,43	high	few	low	1	3	

* Air content in percentage of volume 'kitmasse', spacing factor (s.f.) and specific surface (s.surf.) of air < 2 mm

** Moisture content of near surface (s) and internal (i)

Table 4.5.1.1: Selected material parameters

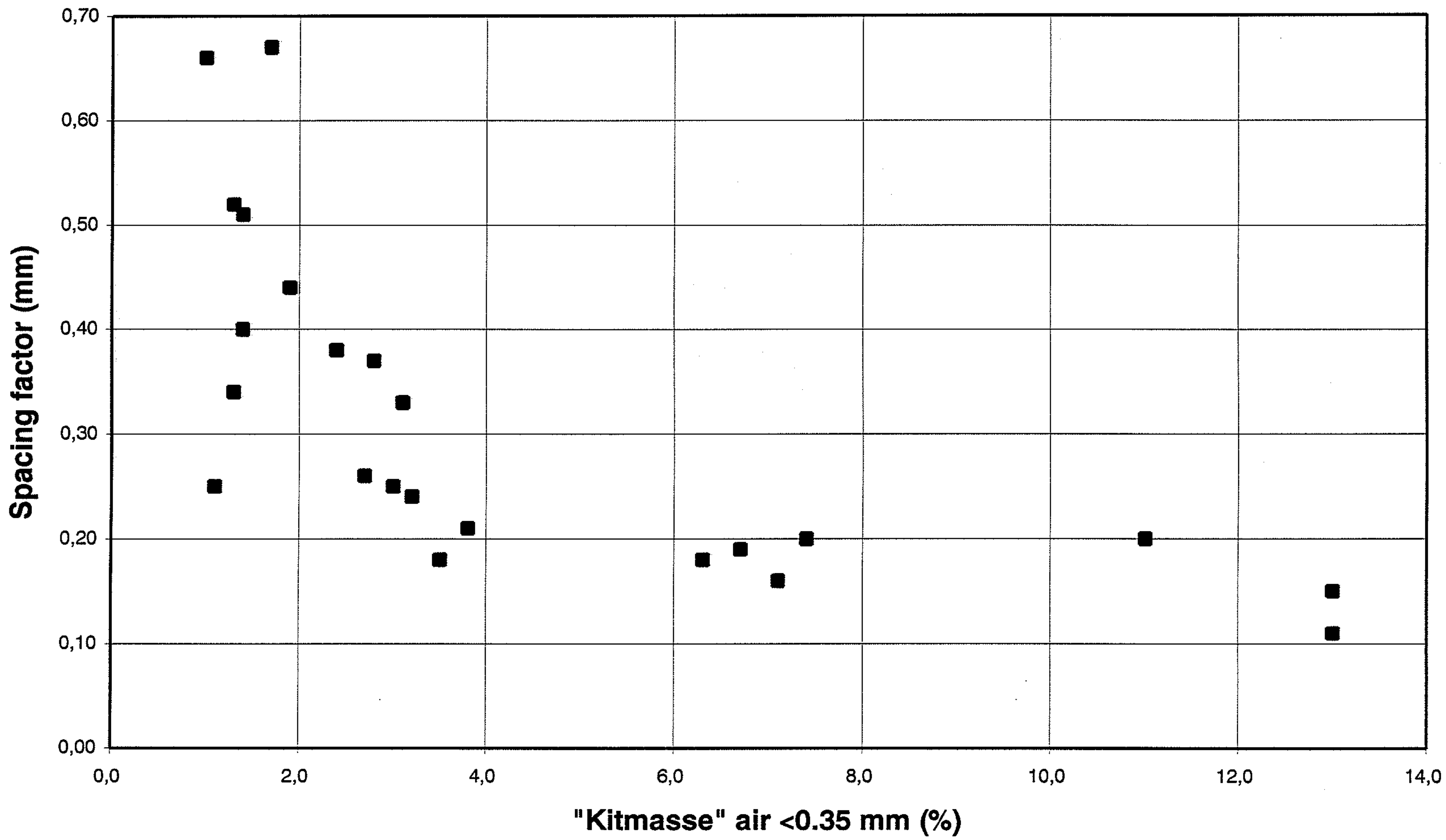

Figure 4.5.1.1: Air content (< 35 mm) versus spacing factor

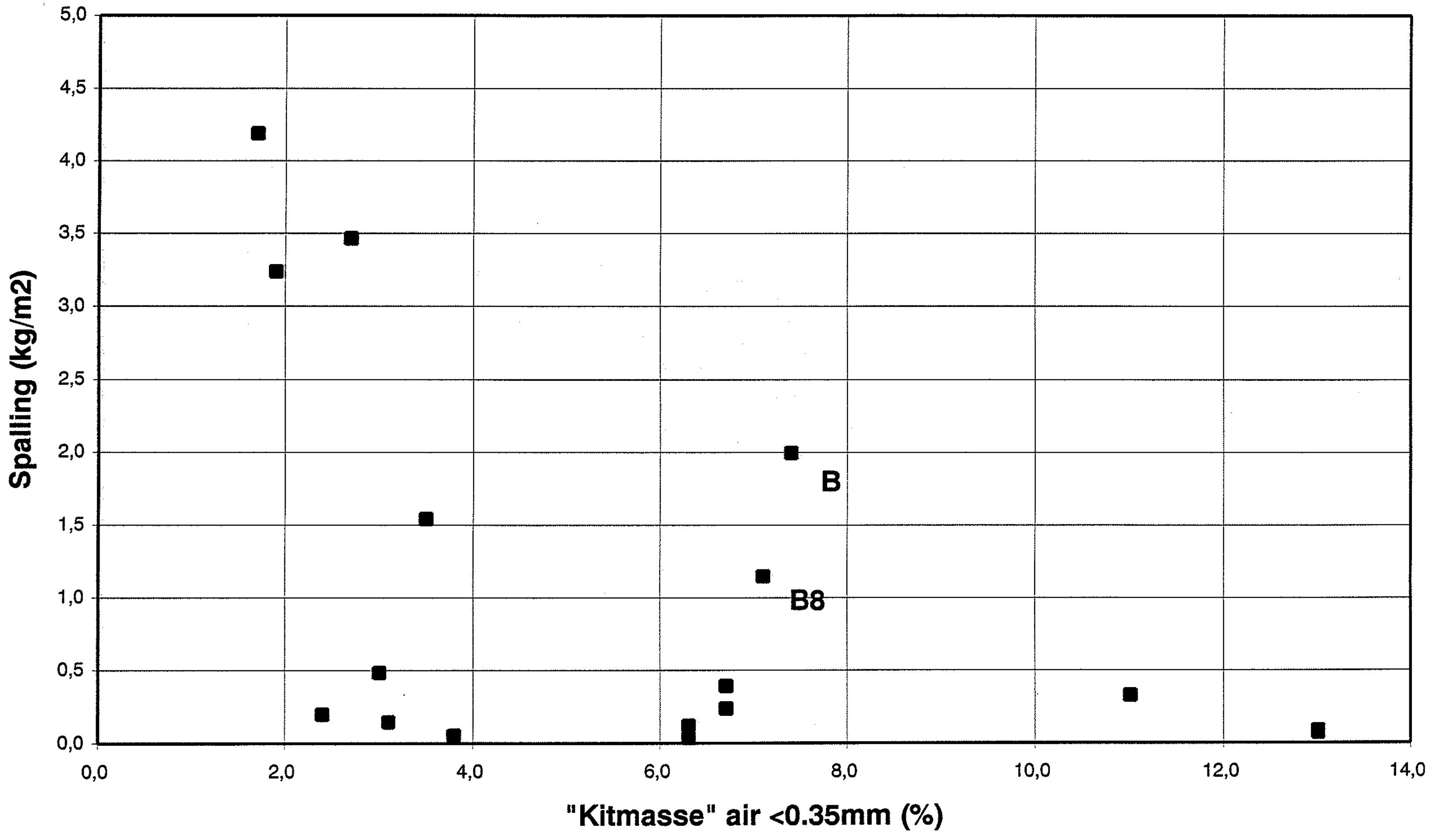

Figure 4.5.2.1: Air content (< 0.35 mm) versus amount of surface spalling (values above 5 kg/m2 not included)

4.5.3 Modified ASTM C 666-A Testing Method

The concretes failing the modified ASTM C 666-A test (expansions exceeding 0.1% after 300 cycles) have less than 6-8% 'kitmasse' air (<0.35 mm), except concrete B29, ref. Figure 4.5.3.1.

The concretes, which pass the modified ASTM C 666-A test (expansions less than 0.1% after 300 cycles) are all air-entrained concretes with higher than 6-8% 'kitmasse' air (<0.35 mm) and a spacing factor of max. 0.20 mm.

4.5.4 Relationship between Moisture Content and Frost Damage

The degree of capillary saturation (summer 1996) versus the degree of in situ damage is illustrated in Figure 4.5.4.1. As expected, it is observed that a high damage degree requires a high degree of saturation.

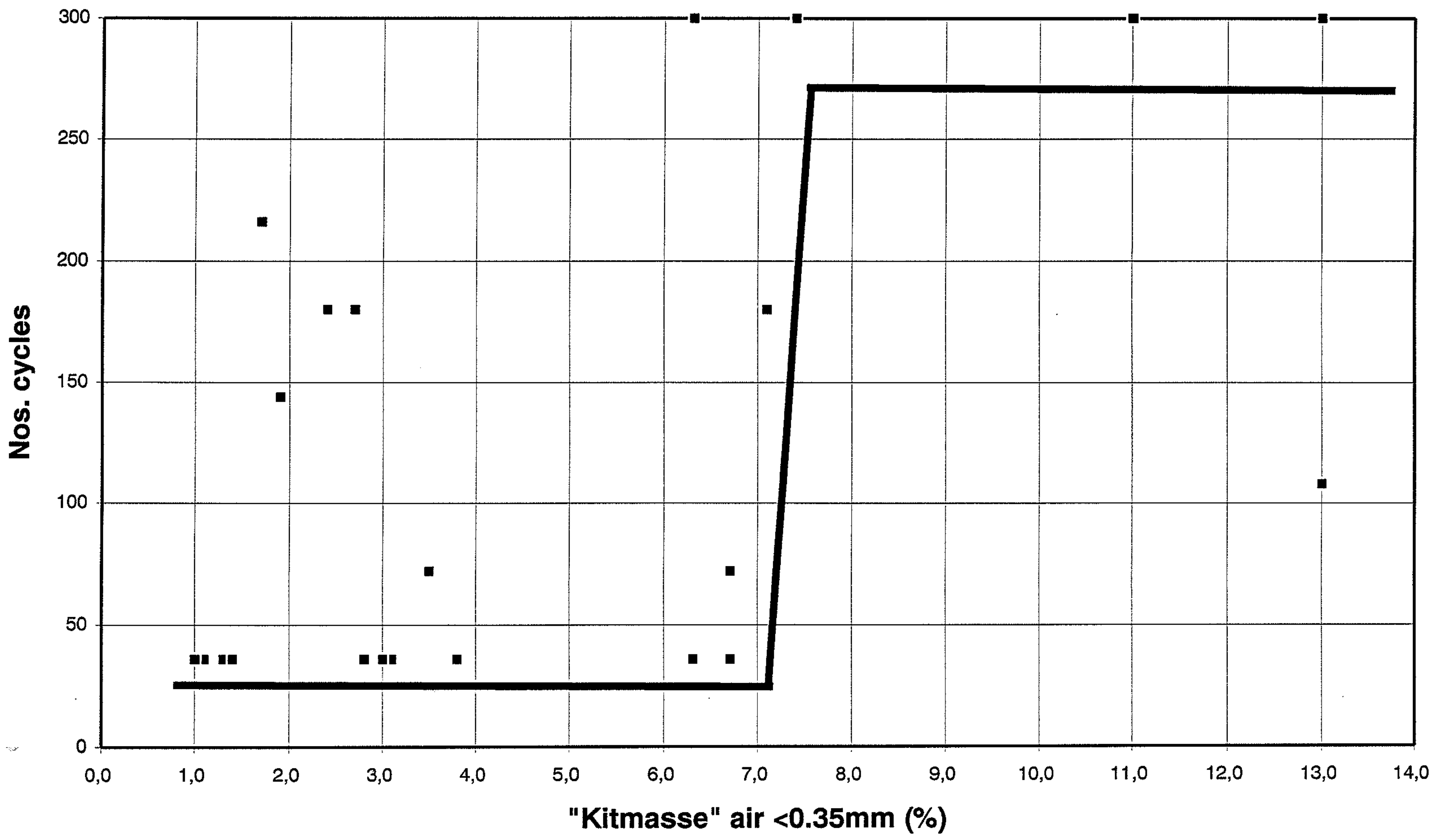

Figure 4.5.3.1: Air content (<35mm) versus number of cycles before 0.1% expansion

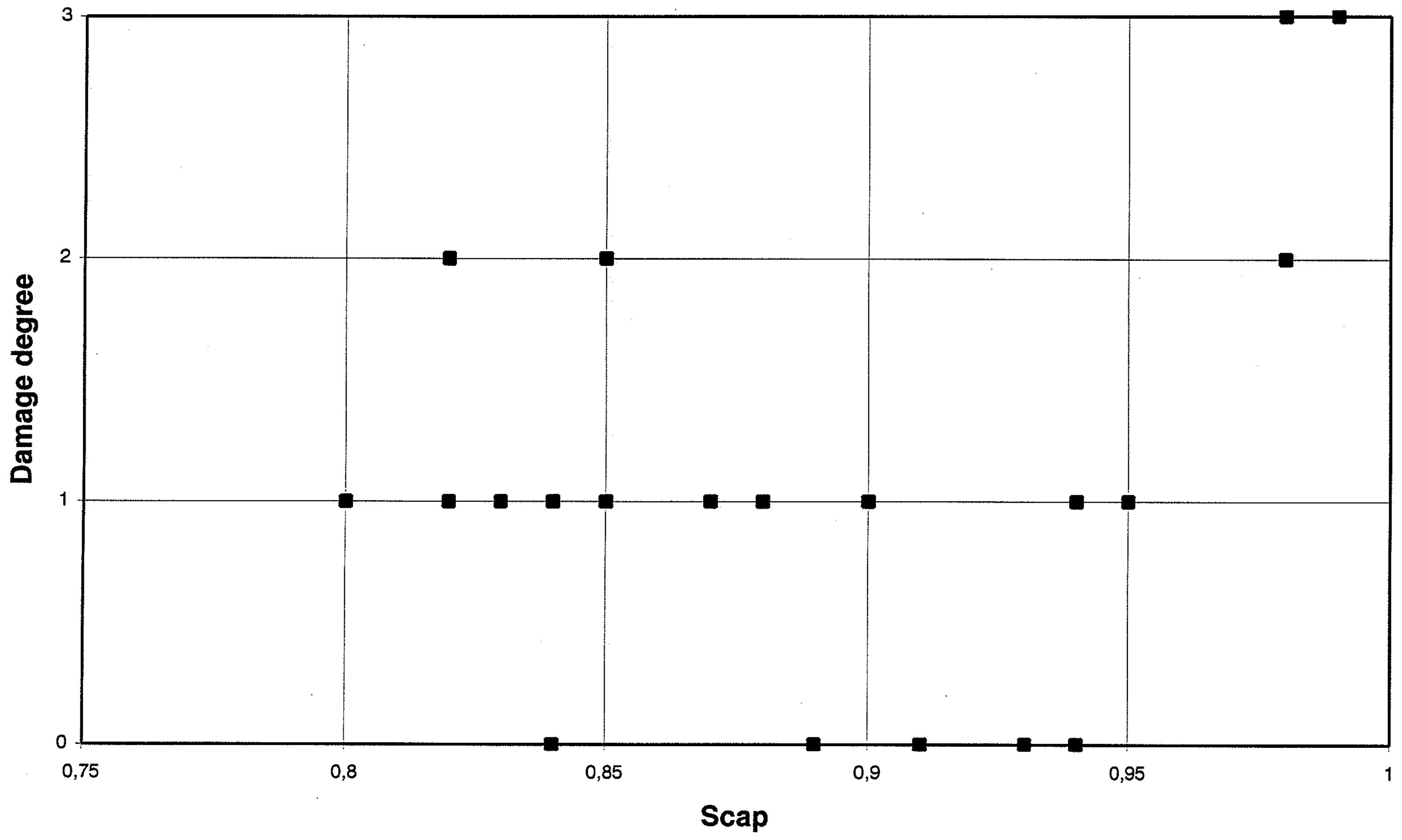

Figure 4.5.4.1: Degree of capillary saturation (Scap) versus in situ damage degree (total)

5 References

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Appendix A

Selected Results

Concrete structure				"kitmasse" air (+corrected)					ASTM C666-mod.		Borås I		Borås II		Moisture											
Sample	Location	Part	build	tot. air	<2mm	<0.35mm	s.f.	s.surf.	expansion	cycles	m56	m56/m28	m56	m56/m28	RH,inne	H,surfa	S-cap,inne	S-cap,surf	-press,I	S-press,	U, inner	U,surfa	U-press,I	U-press,s	Pr,inner.	Pr., surfa
no.			year	(%)	(%)	(%)	(mm)	(mm-1	(%)	nos	(kg/m2)		(kg/m2)		(%)	(%)					(%)	(%)	(%)	(%)	(%)	(%)
B1 V7	Ølby-Ring.	slab	1976	7,5	5,7	2,4	0,38	20	>0.1	252	0,2	1,7	0,1	2,25	94	93	0,95	0,89	0,66	0,72	4,9	4,4	7,4	6,1	31	20
B2 V8	Ølby-Ring.	slab	1976	3,7	3,7	2,7	0,26	38	>0.1	180	3,5	2,8	0,12	3,3	94	89	0,94	0,82	0,62	0,62	5,0	3,7	8,1	6,0	34	24
B3 V2	Ølby-Ring.	slab	1976	10,0	7,6	1,7	0,67	10	>0.1	216	4,2	2,9			93	85	0,95	0,87	0,76	0,66	4,5	3,9	5,9	5,9	20	24
B4 D7	Traff.islnd	deck	1964	26,0	20,0	7,4	0,20	19	0.029	300	2,0	2,9			94	94	0,94	0,93	0,66	0,65	6,6	6,4	10,1	9,8	30	30
B6 S5	B 10-0050	column	1971	1,4	1,4	1,1	0,25	59	>0.1	36	15,0	3	0,53		77	79	0,85	0,83	0,78	0,76	3,8	3,4	4,9	4,5	9	9
B8 K6	Fiskebæk	crash bar.	1981	9,4	9,1	7,1	0,16	39	0.143	180	1,1	11,8	0,02	1,26	78	81	0,94	0,77	0,77	0,52	4,8	3,9	6,3	7,5	17	33
B8 K12	Fiskebæk	crash bar.	1981	9,7	9,8	6,7	0,19	33	>0.1	36	0,2	4,1			98	97	0,94	0,94	0,85	0,82	6,4	7,9	7,6	9,7	10	13
B9 D2	VD106-6004	deck,memb.	1983	12,0	9,5	6,7	0,19	32	0.180	108	0,4	4,4			77	79	0,85	0,72	0,49	0,52	3,4	3,2	6,9	6,1	43	27
B10 D3	VD515-1621	deck	1969	22,0	17,6	13,0	0,15	30	0.019	300	0,1	1,6			74	64	0,84	0,78	0,63	0,56	4,0	4,0	6,2	7,2	25	28
B12 D3	Munkholm	deck	1975	5,6	5,3	3,1	0,33	24	>0.1	36	0,1	2,2	0,03	1,08	73	74	0,85	0,71	0,66	0,49	3,7	2,4	5,6	4,9	22	31
B13 D6	VD515-0151	deck,memb.	1981	19,0	18,6	11,0	0,20	22	0.050	300	0,3	2,2			78	79	0,88	0,79	0,69	0,54	3,0	3,2	4,4	5,8	22	31
B15 BN1	DSB14812	bridge wall	1979	3,9	3,6	3,2	0,24	39	not tested						95	96	0,98	0,97	0,93	0,91	6,3	7,3	6,7	8,0	4	5
B15 BS1	DSB14812	bridge wall	1979	2,3	2,3	1,3	0,34	33	not tested		28,5	1,4			99	97	0,99	1,00	0,95	1,00	6,2	7,8	6,6	7,6	4	3
B16 S3	DSB14832	column	1975	7,3	6,0	3,0	0,25	30	1.326	36	0,5	3			83	75	0,84	0,76	0,73	0,62	5,4	4,8	7,4	7,7	13	18
B17 S8	DSB14829	column	1975	6,9	6,7	3,8	0,21	36	0.136	36	0,1	1,5			85	82	0,85	0,74	0,71	0,61	5,4	4,6	7,7	7,6	16	18
B18 S7	DSB14808	column	1974	5,2	4,3	3,5	0,18	48	0.136	72	1,5	3,9			80	83	0,82	0,74	0,69	0,62	5,1	3,7	7,3	6,0	16	16
B24 D1	M14-0050	edge beam	1953						0.281	72					90	96	0,98	0,96	0,95	0,9	6,4	4,7	6,7	5,2	7	5
B25 S6	Mølleå,bridge	column	1955	4,4	3,3	1,0	0,66	15	1.050	36	32,3	1,9	0,81	2,54	76	64	0,82	0,75	0,72	0,65	3,7	3,3	5,2	5,0	13	14
B26 V1	Borrevejle	retent.wall	1972	2,8	2,6	1,4	0,40	29	not tested						97	82	0,98	0,78	0,91	0,52	8,2	4,5	9,0	8,7	7	33
B27 G2	Farø	crash bar.	1984	12,0	10,5	6,3	0,18	32	0	300	0,1	2,9			79	64	0,89	0,81	0,73	0,57	4,5	3,5	6,1	6,2	18	30
B28 V5	Kastrup,mw	slab	1960	14,0	10,7	1,9	0,44	13	0.111	144	3,2	3,4			92	88	0,91	0,82	0,79	0,73	5,4	5,8	6,9	7,9	14	10
B29 V8	Sydmotorway	slab	1985	14,0	14,3	13,0	0,11	46	0.125	108	0,1	4			84	70	0,93	0,67	0,79	0,4	3,8	3,0	4,8	7,3	15	40
B31 VN2	Glostrp,bridg.	retent.wall	1975	5,0	4,8	1,3	0,52	16	>0.1	36	16,9	4,5	2,15		95	87	0,8	0,68	0,7	0,56	5,8	4,7	8,3	8,4	13	18
B31 VS6	Glostrp,bridg.	retent.wall	1975	8,5	6,2	2,8	0,37	20	0.351	36	5,2	3,5			95	89	0,9	0,7	0,8	0,57	7,3	4,6	9,1	8,1	11	19
B32 VN7	Brøndb,bridg	retent.wall	1980	11,0	9,4	6,3	0,18	34	0.221	36	0,0	1,8	0,13	3,13	87	82	0,83	0,71	0,66	0,53	4,2	3,5	6,5	6,6	21	25
B32 VS1	Brøndb,bridg	retent.wall	1980	5,6	3,4	1,4	0,51	19	>0.1	36	8,9	5,5			85	80	0,87	0,7	0,68	0,59	4,5	3,5	6,6	5,9	22	16

Concrete structure				Microstructure								In-situ observations							
Sample	Location	Part	build	w/c-ratio	inhom.	cracks	ettringite	Moist.eva	evalu.air	eval.	remarks	cracks	spal/pop	Orientation	Rain,Water,	Remarks	In-situ eval.	eval.frost
no.			year	(mean)	(w/c-var.)	fine/coarse	(pore/crack)	pore filling	subj.	micro				Vert./Horin.	Salt		frost	total
B1 V7	Ølby-Ring.	slab	1976	0,35	high	few	high	2	3	1		no	no	H	R,W,S	rough surf.	1	1
B2 V8	Ølby-Ring.	slab	1976	0,38	high	few	low	1	2	1		no	no	H	R,W,S	rough surf.	0	1
B3 V2	Ølby-Ring.	slab	1976	0,35	high	few	high	2	2	1		no	no	H	R,W,S	rough surf.	1	1
B4 D7	Traff.islnd	deck	1964	0,55	low	many	low	2	2	3	early frost	no	no	H	R,W,S	eroded surf.	2	1
B6 S5	B 10-0050	column	1971	0,38	high	few	low	2	2	0		no	yes	V	R	eroded surf.	1	1
B8 K6	Fiskebæk	crash bar.	1981	0,50	low	few	low	0	1	0		no	yes	V	R,W,S	eroded surf.	1	1
B8 K12	Fiskebæk	crash bar.	1981	0,53	low	few	low	1	2	0		no (?)	yes	V	R,W,S	eroded surf.	1	1
B9 D2	VD106-600	deck,memb.	1983	0,38	low	few	low	0	2	0		no	no	H	R,W,S	ok	0	0
B10 D3	VD515-162	deck	1969	0,38	low	few	low	0	1	0		no	no	H	R,W,S	ok	0	0
B12 D3	Munkholm	deck	1975	0,35	high	few	high	2	2	1	ettr. 0-5mm	no	yes	H	R,W,S	eroded surf.	2	2
B13 D6	VD515-015	deck,memb.	1981	0,38	high	few	low	1	1	0		no	no	H	R,W,S	rough surf.	0	0
B15 BN1	DSB14812	bridge wall	1979	0,60	low	many	high	3	3	3	frost	yes	no	V	R	efflor.	3	3
B15 BS1	DSB14812	bridge wall	1979	0,60	high	many	high	3	3	3	frost	yes	no	V	R	efflor.	3	3
B16 S3	DSB14832	column	1975	0,38	high	few	low	1	2	0		no	no	V	R	rough surf.	1	1
B17 S8	DSB14829	column	1975	0,43	low	few	low	1	2	0		no	no	V	R	rough surf.	1	1
B18 S7	DSB14808	column	1974	0,45	high	many	low	1	2	1	frost	yes	no	V	R	eroded surf.	1	1
B24 D1	M14-0050	edge beam	1953					ot tested				yes	yes	V	R		2	2
B25 S6	Mølleå,bridg	column	1955	0,38	high	few	low	1	3	0		no	no	V	R	ok	0	0
B26 V1	Borrevejle	retent.wall	1972	0,45	high	many	high	2	3	3	frost+ASR	yes	no	V	W*	eroded surf.	1	3
B27 G2	Farø	crash bar.	1984	0,33	low	few	low	0	0	0		no	no	V	R,W,S	ok	0	0
B28 V5	Kastrup,mw	slab	1960	0,43	high	few	low	1	3	1		no	no	H	R,W,S	ok	0	1
B29 V8	Sydmotorw	slab	1985	0,38	high	few	low	1	0	0		no	no	H	R,W,S	ok	0	0
B31 VN2	Glostrp,brid	retent.wall	1975	0,43	high	few	low	1	3	1		yes	no	V	R	map crack.	1	1
B31 VS6	Glostrp,brid	retent.wall	1975	0,48	high	few	high	2	3	1		yes	no	V	R	map crack.	1	1
B32 VN7	Brøndb,brid	retent.wall	1980	0,40	high	few	low	1	1	1		yes	no	V	R	map crack.	1	1
B32 VS1	Brøndb,brid	retent.wall	1980	0,43	high	few	low	1	3	1		no	no	V	R	map crack.	1	1

Appendix B

Procedure for the Borås method SS 13 72 44 (1995), testing on concrete cores, procedure III as performed in the HETEK project

Specimens

The specimens are 50 mm slices sawed from cylinders with a diameter of 100 mm and a length of up to 200 mm. Depending on the presence of reinforcement it has been possible to cut two slices from each of the three specimens available.

Immediately after coring the specimens are thoroughly washed, surfaces are wiped with a moist cloth and wrapped water and vapour tight in plastic foil. The specimens are placed in a room with 20 °C ± 2 °C and 65 % ± 5% relative humidity until sawing.

Conditioning

After sawing the specimens are stored in this climate for 7 days. During this period a water tight layer of 3 mm rubber is clued at the bottom and at the cylindric surface with a hight establishing a 20 mm wall over the surface to be exposed. The edge between the exposed surface and the wall of rubber is especially water tightened with a string of silicone. Outside the rubber layers a layer of 20 mm insulating foam (DOW mats) is placed.

After the 7 days the surface to be exposed is covered with a 3 mm layer of demineralized water for 3 days.

Just before the freeze/thaw testing this water is replaced with a layer of 3 mm 3% NaCl solution and a thin polyethylene plastic is stretched over the top to prevent evaporation.

Freeze/thaw test

The specimens are placed horizontally in the freeze/thaw chamber positioned in such a way that the same even temperature distribution is obtained around all specimens.

The temperature recording used for controlling is placed on two dummies similar to the concrete tested. The average temperature recorded is used as signal for controlling the temperature to be within the temperature limits prescribed by the method. By using a computer controlled system it is possible to place the temperature very accurately within the limits as shown in the figure.

After 7, 14, 28, 42 and 56 cycles with a duration of 1 day the weight of material spalled from the exposed surface of each specimen is measured by the following procedure:

The material is collected by soft water spraying in a coffee filter and the surface is cleaned with a soft brush. The material is dried out in an oven at 105 °C for 1 day.

Borås, Modified Conditioning

The Borås method with modified conditioning follows the same procedure when testing freeze/thaw. The modification is mainly the conditioning before the actual test procedure. In order to be able to measure possible internal cracking two sets of gauge studs of stainless steel are placed perpendicular to each other on the cylindrical surface. One 15 mm from the top the other 25 mm from the top. These studs are placed in drilled holes to the depth of 5 mm and glued with strain gauge glue. The studs are placed through holes in the rubber layer water tightened with silicone. In the insulating material holes forming stoppers are cut over each stud giving enough place for the equipment measuring the length change, when they are removed during the measurement. This is done after a period securing, that the temperature is in equilibrium with the surroundings (20 °C) and with an accuracy of 1/100 mm.

TMS for Windows
DTI Building Technology

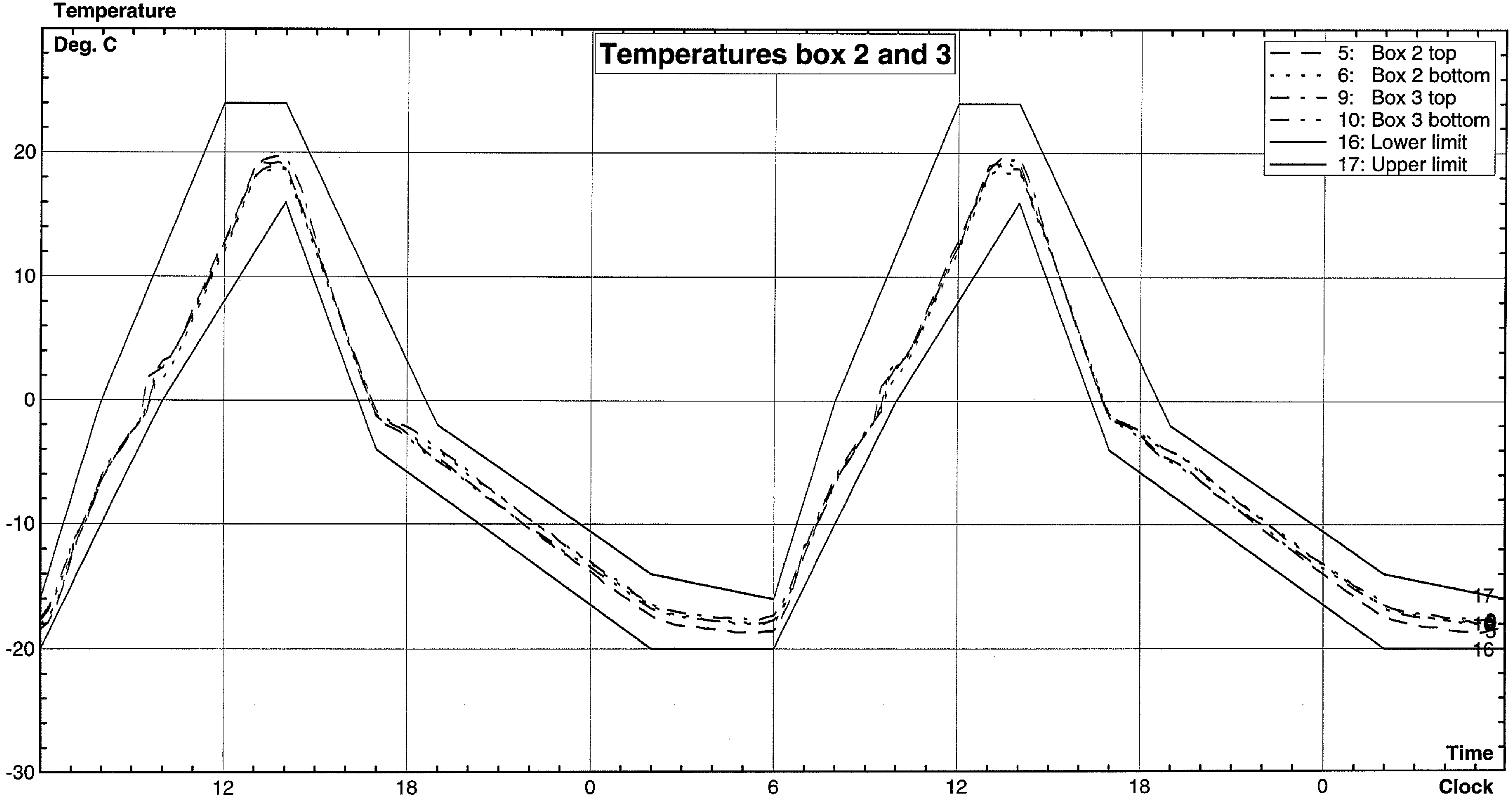
DTI Frost-testing
Connection: E17B

Client: HETEK - Frost
Contact: ejp

Reference: SS 13 72 44 Boraas
Initials: jlf

Project: DTI - HETEK
File: aug. - oct.

Date: 1997-02-27
Time: 08:59



Total records: 4117
Datafile: q:\jlf\tmswin\e17b.dat

Log period: 20-08-96 11.45 to 02-10-96 08.45
Plot period: 13-09-96 06.00 to 15-09-96 06.00

Appendix C

Procedures of the Modified ASTM C 666-A testing for the HETEK project

Specimens

The specimens are drilled concrete cores (diameter: 100 mm ±5 mm, Length minimum 200 mm).

Immediately after coring, the specimens are thoroughly washed, surface dried with a moist cloth and wrapped water and vapour tight in plastics.

At arrival at the lab, the cores are unwrapped, and cut to length, 135-140 mm. If the outer end of the core is without any defects or notable carbonation, the specimen can be placed from the exposed surface and inwards. Otherwise the specimen must be placed deeper in the core to achieve an undamaged specimen.

During the handling of the cores no drying out is accepted. All treatment involving water, i.e. cooling water during sawing and drilling, must be followed by thorough washing of sludge and subsequent surface drying by use of a moist cloth.

The specimen is mounted with gauge studs centrally in both ends, according to the following procedures:

* The core is placed in the drill stand and a hole is drilled with a 10 mm diamond core drill using water cooling. The depth of the holes must be 16 mm ± 2 mm. The central small core plug is gently removed. The holes are dried with high pressure air.

* In each hole a gauge stud is mounted, ref. Figure 1. The stud is placed centrally in the plastic cap with double-stick-tape. The core is placed vertically. The upper hole is filled to 3 mm from the top with rapid hardening *X-60 strain gauge glue*, without getting glue on the surface. Readily the plastic cap with the gauge stud is placed centrally over the hole, and the stud is lowered until the plastic cap stands on the core end, ref. Figure 1.

* The core remains vertical for at least 30 minutes, and the plastic cap is gently removed by pressing a blade between its rim and the concrete surface. After mounting the gauge stud the core must never be placed directly on the end.

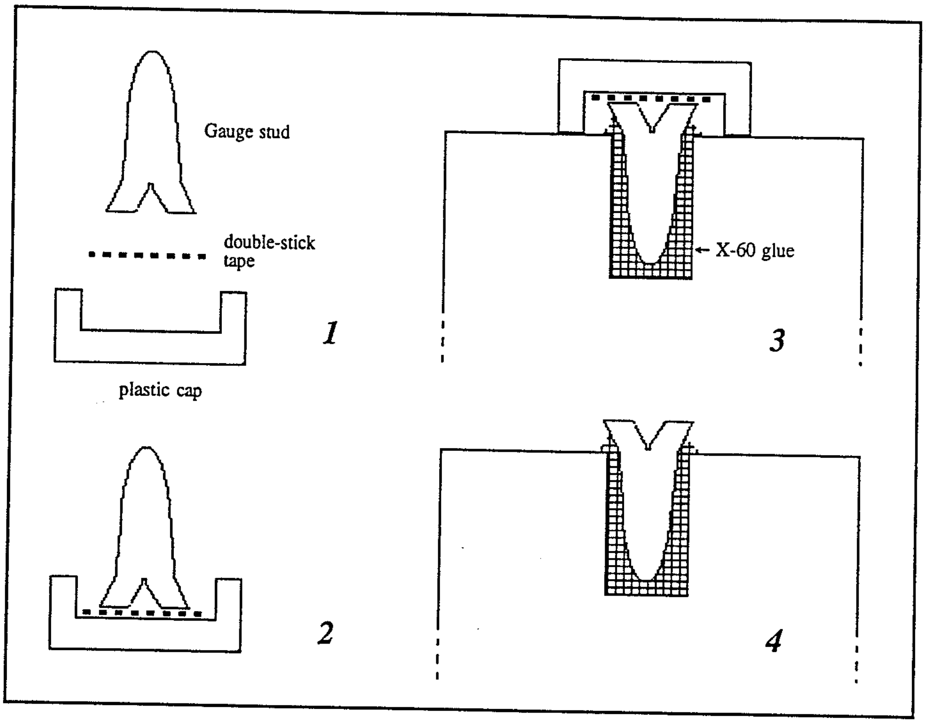


Figure 1 Mounting of gauge stud in the core.

Conditioning

No actual conditioning is carried out, yet the cores are secured against drying out and kept at 20 °C.

Freeze/Thaw testing

The freeze/thaw testing is initiated and run for 300 freeze/thaw cycles or until the set requirements for expansion is exceeded. Automatically, the frost liquid temperature is changed to achieve a central temperature in the specimens varying from +4.4 °C to -17.8 °C (both ±1.7 °C), within a cycle time of 3.6 hours. After each 36 freeze/thaw cycles the specimens are measured.

The general set-up of the freeze/thaw equipment fulfills the ASTM C 666 requirements, ref. Table 1. The frost liquid ('Antifrogen N') containing freeze/thaw-vessel can store as much as 120 specimens. The Vessel is mounted with an upper steel frame above the frost liquid for fixation of the specimens. To secure even temperature cycles, the frost liquid is by pumping replaced 0.5 times per minutes.

Table 1. ASTM-C 666 definitions and requirements.

Parameter	Definition	Requirements	DBT-procedures	Requirements fulfilled
freeze/thaw cycle [hours]	Time: T_{max1}-T_{max2}	2 - 5	3,6	yes
$Temp_{max}$ [°C]	Maximum temp. as measured centrally in concrete dummy	4.4 ±1.7	2.8	yes
$Temp_{min}$ [°C]	Minimum temp. as measured centrally in concrete dummy	÷17.8 ±1.7	÷17.5	yes
TP: thawing period [hours]	$T_{min} \rightarrow T_{max}$	TP ≥ ½·VP TP ≥ ¼·Cycle	1.6 ≥ ½·1.2 1.6 ≥ ¼·3.6	yes yes
FP: freezing period [hours]	$T_{max} \rightarrow T_{min}$	FP ≥ ½·KP	2.0 ≥ ½·2.4	yes
HP: heating period [hours]	The heating time of the system (frost liquid vessel)	---	1.2	---
CP: cooling period [hours]	The cooling time of the system (frost liquid vessel)	---	2.4	---
Specimen size [mm]	Length: L Width: W (Diam.) [mm]	L: 279 - 406 B (D): 76 - 127	L: 150 D: 95-105	no
Specimen maturity [M-days]	-	(14 M-days for cast specimens)	normally ≥ 28	yes
Specimen conditioning	-	Specimens from structures may not dry more than in the structures.	No drying	yes
Test liquid [mm]	Thickness of tap water layer	1-3	1-2	yes
End of test	No. of cycles, length change: ΔL, or Relative E_{dyn}	300 freeze/thaw cycles, ΔL ≥ 0,10% or E_{dyn}-rel ≤ 0,60	same (or as specified in given requirements)	yes

Preparing the Specimen For freeze/thaw Testing

The specimen is prepared for freeze/thaw testing by the following procedures:

* The top and bottom of the core is covered by a 5 mm thick styrofoam protection, having the same diameter as the core. The core and styrofoam protection is placed in a spacer net ('Aksel-net: 2C Blue'), ref. Figure 2.

* The specimen is placed in a strong plastic bag ('Codex: 650 x 200 x 0.15 mm PVC, special welded seams') which is being held tight to the specimen/spacer net, by surrounding strips of 50 mm broad scotch tape, placed at the bottom, middle and top of the specimen. The bottom part of the plastic bag is likewise held tight to the specimen with scotch tape.

* The wrapped specimen is placed in a protection net ('Aksel-net: 2A Black') covering bottom and sides.

* The plastic bag is poured with test liquid - tap water - until 2-3 mm above the top surface of the specimen. The thickness of the test liquid layer is 1-2 mm, as secured by the spacer net and the protection net.

* The wrapped, secured, and test-liquid-covered specimen is placed in the freeze/thaw-vessel. The top of the plastic bag reaching at least 100 mm over the level of frost liquid, is fixed to the upper steel frame - care is taken to prevent a frost liquid flush of the specimen. The specimen must be fully below the level of frost liquid.

Measuring the Specimen Length

The specimens are measured before start of freeze/thaw testing, and subsequently after each 36 freeze/thaw cycles until the testing is terminated.

The length measurements are carried out within 5 min at a laboratory temperature of 20 °C. The specimens have a temperature of 8 °C ±2 °C, corresponding to the 'resting temperature' of the freeze/thaw system.

The specimen is carefully removed from the frost liquid containing freeze/thaw-vessel. The tap water test liquid is poured off. The protection net and plastic bag is removed, and the spacer net is carefully pulled off.

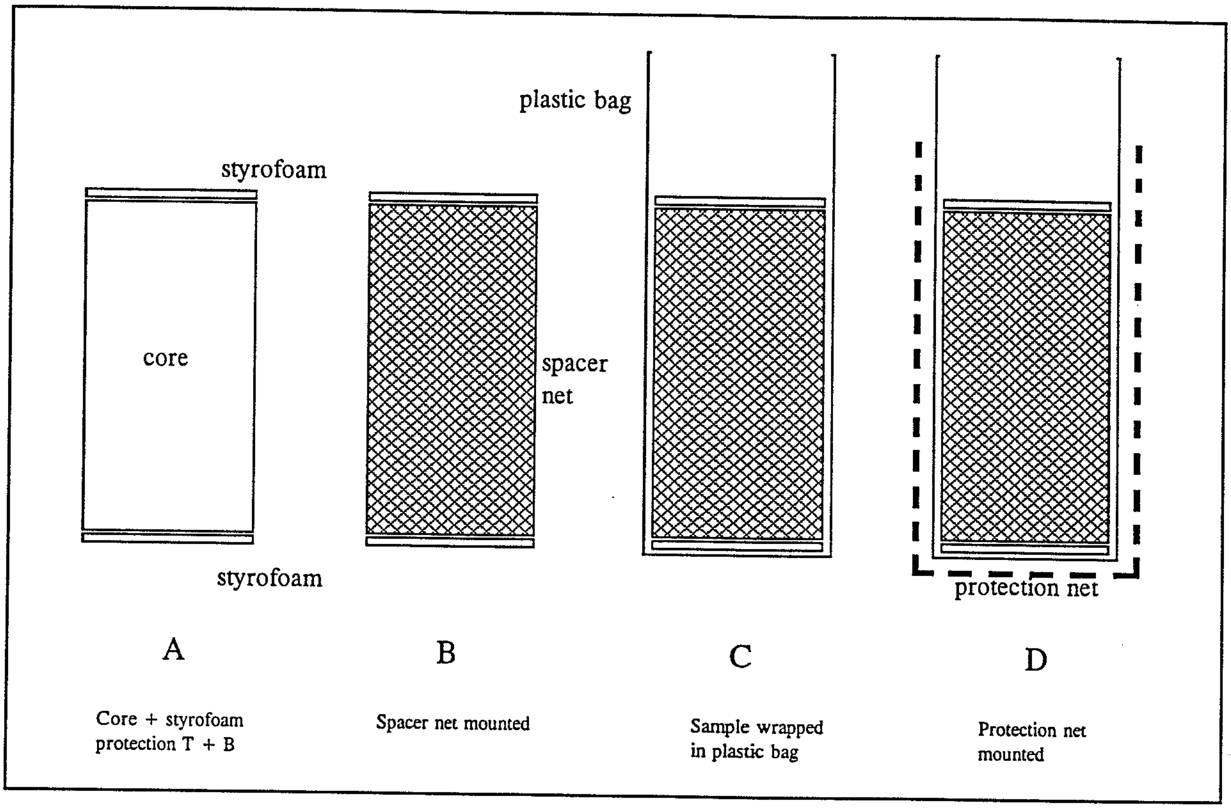


Figure 2 The wrapping procedures for specimens to be freeze/thaw tested.

The length measurements are carried out according to the following procedures:

* The specimen is gently surface dried with a damp cloth. The gauge studs are blown dry.

* The specimen is placed in the precision dial gauge stand - at each measurement the specimen is placed the exact same way. The reading of the precision dial gauge is repeated to ensure a reproducible result. The length is recorded.

* The specimen is scrutinized with naked eye, and with hand lens. All observations, such as crumbling of paste, cracks, pop-outs, general expansion, discolouration a.o. are recorded.

The specimen is readily wrapped for, test liquid (tap water) is added, and the specimen put back in the frost liquid containing freeze/thaw-vessel for further testing.

Test Results

The expansion is computed according to:

$$\text{Expansion} = \Delta l/L_0 \times 100\ \%$$

where

L_0: Specimen length (in mm) before exposure

l_0: Reading on precision dial gauge (mm with 3 digits) after 0 freeze/thaw cycles.

l_i: Reading on precision dial gauge (mm with 3 digits) after i freeze/thaw cycles.

Δl: $l_i - l_0$

Reporting

General information is reported. Furthermore, the following parameters are reported for each set of specimens, for each measure term:

- dial gauge reading for each specimen,
- computed expansion for each specimen,
- mean expansion for the set of specimens,
- visual observations for each specimen,
- graph depicting the expansion history of each specimen