HETEK

Method for test of the Frost Resistance of High Performance Concrete

Summary, Conclusions and Recommendations

Report No.97
1997

Road Directorate Denmark Ministry of Transport

IRRD Information

Title in Danish	**HETEK, Frostprøvningsmetoder til bestemmelse af Højkvalitetsbetons Frostbestandighed. Opsummering, Konklusion og Anvisning.**
Title in English	**HETEK, Method for test of the Frost Resistance of High Performance Concrete. Summary, Conclusions and Recommendations.**
Authors	Anders Henrichsen, Peter Laugesen, Mette Geiker, Erik Jørgen Pedersen, Niels Thaulow

Subject Classification	Concrete	32
Keywords	Absorption	6758
	Cracking	5211
	Deterioration	5255
	Drying	5184
	Freezing Thawing Cycle	2577
	Frost Damage	5278
	Gradient	2806
	Ice	2578
	Micro	9045
	Moisture Content	5920
	Porosity	5938
	Research Project	8557
	Salt	2598
	Saturation	9125
	Spalling	5231
	Stress Analysis	5573
	Structure	5937
	Test Method	6288

UDK 691.32
666.972.5

ISSN 0909-4288

ISBN 87-7491-807-9

Table of Contents

1 Summary

1.1 Introduction

1.1.1 A general View of Freeze-Thaw Testing of Concrete

The resistance of concrete against freeze-thaw attacks is one of the major uncertainties in the assessment of lifetime of concrete structures. Reliable models for the verification of a predicted/prescribed service life in relation to frost and frost-salt deterioration of High Performance Concrete are needed but, unfortunately, at present not available.
This need has been further enhanced by the present trend among designers to predict and request lifetime for concrete structures exceeding 100 years even in severely exposed environments.
Analyses of Danish and international concrete specifications and standards indicate that even for structures with very long lifetime expectations provision of freeze-thaw and deicing salt resistance has been achieved mostly through a prescriptive approach, i.e. by defining the mix design; the water/cement ratio, the minimum content of entrained air or the spacing factor, the quality of the constituents of the concrete and the manufacturing process.
Such procedures have often resulted in structures of which it is believed that the lifetime expectations regarding frost resistance will be met, which confirms the relevant of these specifications.
Direct testing of freeze-thaw resistance is, however, very seldom required in international specifications and if so primarily as a measure to be applied during pretesting of concrete.
This is believed to be caused by the rather poor reliability and reproducibility of test procedures reached to date. Further, there seems to be a complete lack in the international research in regard to correlation between test results obtained during pre-testing and corresponding testing of samples from exposed structures.
Therefore, approval or rejection of structures based on direct testing of freeze-thaw resistance is difficult; Precise and reliable test procedures are urgently needed.

1.1.2 Background, HETEK Task 2, Frost Resistance of Concrete

The present research is part of a research and development programme entitled HETEK, Højkvalitetsbeton - Entreprenørens Teknologi (High Performance Concrete - Construction Technology). The research has been carried out under the auspices of the Danish Agency for Development of Trade and Industry. The title of the present task 2 of the research contract is: "Test Methods for Determining the Frost Resistance of High Performance Concrete".
The research is carried out by a consortium consisting of Dansk Beton Teknik A/S, Dansk Teknologisk Institut and Dansk Betoninstitut a/s.

High Performance Concrete is defined by the Road Directorate as "a concrete with an expected life of 100 years in an aggressive environment".
The consortium has for use during the research period elaborated this definition of HPC as follows:

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

The results of the research are presented in the following reports:

Report no. 55, 1996; State-of-the-art
Report no. 86, 1996; Supplementary Research
Report no. 93, 1997; Performance Testing versus In Situ Observations
Report no. 97, 1997; Summary, Conclusions and Recommendations

1.1.3 Research Approach

It was concluded (above, section 1.1.1) that material scientists have not yet succeeded in developing operational models of freeze-thaw deterioration or frost resistance of concrete structures.
It has further been concluded that a relationship between performance of structures and test results obtained on either samples taken in the structures or laboratory cast specimens has not been established.
Direct testing based on existing test method statements applied to concrete from structures has only been reported to a very limited extent.

The research approach is, therefore, in the first phase aimed at searching for a correlation between results of a given test method and the actual frost resistance of a large number of concrete structures for which it is possible to establish

I) The degree of exposure
ii) The degree of frost resistance or deterioration

It is in this context important to realize that there for the structures exists a large variety of different kinds of freeze-thaw and deicing salt attack.
Concrete reacts to the different kinds of exposure depending on its composition, constituents and age.
At least two different reactions can be established:

- frost damage in form of scaling
- internal frost damage

As a consequence the research has indicated that more than one test method should be applied in the assessment.

Any test method to be chosen for introduction in this research should, however, reflect the fact that the major factor determining the frost resistance of a certain frost exposed concrete in practice is the maximum degree of saturation occurring in the structure in relation to critical degree of saturation.

Based on the consideration summarized above the following research approach was chosen:

1. Selection of one or more test methods considered relevant for application on Danish concrete structures based on a State-of-the-art assessment

2. Verification of the feasibility of the selected methods through a limited supplementary research phase

3. Selection of a number of concrete structures meeting the following criteria:

    a. Capillary porosity of the paste in the concrete shall correspond to that of a paste with w/c- ratio in the range of 0.35 - 0.45 at 28 days maturity

    b. Classification of the degree of frost resistance deterioration shall be possible with a reasonable representativity for the structural element in question.

    c. The selected member shall not show signs of other types of deterioration i.e. corrosion damage, alkali aggregate reactions or other.

    d. The structures shall include examples of both scaling and internal damage deterioration.

    e. The selected structures shall represent at least 3 deterioration levels i.e.:
    - no frost deterioration
    - some frost deterioration
    - severe frost damage

f. The selected structures shall have been exposed to frost and their environment or microclimate shall represent levels of
- severe moisture exposure
- moderate moisture exposure
- limited moisture exposure

4. Documentation of a system for classification of degree of deterioration.

5. Documentation of a system of exposure classes.

6. Sampling of concrete from non-deteriorated parts of the structures.
Sampling concrete in deteriorating zones for verification of the visual assessment by petrographic analysis.

7. Final classification of the degree of deterioration.

8. Classification of the exposure class of the selected structures.

9. Frost testing of samples.

10. Evaluation of test results, acceptance of test methods and proposal of acceptance criteria for freeze-thaw testing of concrete sampled in a structure.

11. Preparation of Guidelines for freeze-thaw testing of concrete during pretesting and for concrete in the structures.

12. Preparation of recommendations for verification of criteria for frost resistance in accordance with the HETEK Guidelines for Freeze-thaw testing of concrete.

1.2 Description of the Research

1.2.1 Objectives

A contract was awarded for task 2 of the HETEK research programme on December 21, 1995.
The research was completed by March 31, 1997.

Based on the State-of-the-art investigation, March 1996 and the Supplementary research, August 1996 the main task, Performance Testing vs. In Situ Observations was initiated in August 1996.
The objectives of the research were defined in accordance with the research approach:

- To suggest a deterioration classification system

- To suggest an exposure class rating

- To provide information on the applicability and suggest acceptance criteria for the following selected accelerated frost testing methods:

  * The Borås Method, SS 137244, 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 (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 conditioning and material characteristics.

- To assess the applicability of a supplementary method for evaluation of frost susceptibility through determination of the Pore Protection Ratio.

1.2.2 Presentation of Results

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.

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

1.3 Conclusions

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.

1.3.1 SS 137244, 1995 (III)

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

Only one type of concrete with a scaling after 56 freeze/thaw cycles below the indicated criterion for frost susceptibility was classified as deteriorating in situ. However, as the scaling in this concrete was only 0.1 kg/m^2 with small standard deviation in the frost test it has been concluded that there did not exist any correlation between the material quality tested and the quality of the material in the structure which caused a classification "deteriorating".
The criterion suggested corresponds to the requirements applied in the Swedish standard specification for bridge structures.
It is recommended that the requirements is given attention during the verification phase.
It is further enhanced that the probability of accepting /rejecting concrete with improper /proper in situ performance should be selected by the owner.

Requirement 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 it is tentatively suggested that the same requirement is applied for drilled cores from structures in exposure class 2 whereas the present investigations cannot be applied as a basis for formulation of any requirements to in situ concrete in exposure class 3.

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.

1.3.2 ASTM C 666, Procedure A (Modified)

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 investigations 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 the environmental impact of class 2 and class 3 exposure does not result in critical degrees of saturation of the concrete, the method is not regarded relevant for these exposure conditions.

1.3.3 Pore Protection Ratio

The testing of pore protection ratio is recommended for use 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 the following requirement for the pore protection ratio in cores drilled from concrete structures in exposure class 1 is tentatively suggested:

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.

1.3.4 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.

1.3.5 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.

1.3.6 Conditioning of Samples

General

When the above suggested test methods are used for assessing the frost susceptibility of a concrete structure the test specimens will always be cored samples from the structure.

Testing of the structures at maturities of the concrete less than 28 days is not considered.

Therefore, a special pre-conditioning phase will not be required for such testing. When the proposed test methods are applied in pre-testing of a material it may be assumed that the concrete is produced in the laboratory.
A clear procedure for the moist curing of such specimens (pre-conditioning) will be required as described below.

Curing (Pre-conditioning)

The present guidelines will preferentially adopt the Danish curing procedures for Borås testing, ref. Appendix 1. This will facilitate the application of the method in Denmark.

The Danish methods for testing hardened concrete generally prescribes the following curing procedures:

- casting of cylinders, demoulding after 1 day
- water curing from time of demoulding until testing

The Swedish methods for testing hardened concrete, hence also the Borås method SS 137 244, generally prescribes the following curing procedures:

- casting of cubes, demoulding after 1 day
- water curing for 6 days
- storage in laboratory atmosphere (40-80% RH, 15-25°C) until testing

The influence of changing the curing ('pre-conditioning') procedures for the Borås testing has to be assessed. The sparse documentation [Geiker et al., 1996] indicate that changing between the above two curing types have little or no influence on the frost resistance of high performance concrete, whereas there may be some impact on the results for concrete with higher capillary porosity, e.g. for water/cement ratios above 0.45.

Test Conditioning

The conditioning of test specimens for freeze/thaw testing has been the subject of much debate.

The influence of the Borås test-conditioning,i.e. drying (65% RH, 20°C) and re-saturation, resulted in a slight decrease in moisture content of the samples. Tests with harsher test- conditioning, e.g. drying (10% RH, 50°C) and re-saturation, caused a further decrease in moisture content.

The influence of the two types of test-conditioning on the frost resistance was investigated on samples from in-situ structures. This showed that the harsher test-conditioning gave less (or similar) scaling. Hence, it may be concluded that testing without initial drying give the harshest testing.

The results of the HETEK research indicate that for high performance concrete with equivalent W/C ratio of 0.35-0.45, variations in conditioning for testing have neglectable influence on the freeze/thaw results.

For reasons of harmonization between the Nordic countries, the test condition which is prescribed in the Borås method (SS 137 244) is retained.

1.4 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

2 Guidelines for Testing of Frost Resistance of Concrete

2.1 Introduction

The assessment of frost resistance of high performance concrete are carried out according to the following procedures:

i) classification of the structure into exposure class, ref. chapter 2.2
ii) selecting the relevant test methods, ref. chapter 2.3
iii) selecting the relevant acceptance criteria, ref. chapter 2.4.

The guidelines are intended for use during pretesting of concrete as well as for documentation of frost susceptibility of structures.

2.2 Classification of Structures into Exposure Classes

The 3 exposure classes are defined according to the following criteria:

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

2. Structures exposed to frost and sometimes 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.

2.3 Recommended Test Methods

The test methods to be applied for the assessment of frost resistance of high performance concrete are:

- Borås for frost scaling, ref. Appendix 1
- Modified ASTM, for internal cracking, ref. Appendix 2
- Pore Protection Ratio for moisture saturation, Ref. Appendix 3

The prescribed test methods for a specific concrete, i.e. exposure class, are given in table 1.

Table 1. Prescribed test methods for assessment of frost resistance.

Exposure class 1	Exposure class 2[note 1]	Exposure class 3[note 1]
Borås[note 2]	Borås	(Borås)[note 3]
Mod. ASTM C 666-A	n/a	n/a
Pore Protection Ratio[note 4]	n/a	n/a

Note 1: Concrete structures of exposure classes 2 and 3 must be upgraded to exposure class 1, if:
- the structures are impossible to repair
- the exposure can change during use or deterioration of the structure

Note 2: The Danish curing procedures will preferentially be adopted, ref. Appendix 1.:
- casting of cylinders, demoulding after 1 day
- water curing from time of demoulding until testing

The influence of this change of the curing procedures for the Borås testing has to be assessed. The sparse documentation [Geiker et al., 1996] indicate that changing between the above two curing types have little or no influence on the frost resistance of high performance concrete.

Note 3: Borås may be relevant for exposure class 3 during pre-testing. However, there are no indications in the present research, that structures in exposure class 3 are frost susceptible.

Note 4: The Pore Protection Ratio is included for pretesting as supplementary information.

2.4 Recommendations to Acceptance Criteria

Exposure Class 1

The recommendations for acceptance criteria for the prescribed frost resistance testing of exposure class 1 is given in table 2.

Table 2 Proposal for acceptance criteria in exposure class 1.

Test Method	Pretesting	In Situ Testing
Borås	$m_{56} < 0.2$ kg/m^2 or $m_{56} < 0.5$ kg/m^2 and $m_{56}/m_{28} < 2$	$m_{56} < 1.0$ kg/ m^2 note 1
Mod. ASTM C 666-A	expansion$_{300}$ < 0.05 %	expansion$_{300}$ < 0.1 %
Pore Protection Ratio	min. 25 % note 2	n/a

Note 1: This requirement may be changed, e.g. to 0.5 kg/m^2. However, the present documentation does not indicate the need for such change.

Note 2: The Pore Protection ratio may be considered to be for information. However, if the set value is not conformed with, futher documentation of the frost resistance is required.

The probability of accepting/rejecting concrete with improper/proper in situ performance should be selected by the owner.

Exposure Class 2

The recommendations for acceptance criteria for the prescribed frost resistance testing of exposure class 2 is given in table 3.

Table 3 Proposal for acceptance criteria in exposure class 2.

Test Method	Pretesting	In Situ Testing
Borås	$m_{56} < 0.2$ kg/m^2 or $m_{56} < 0.5$ kg/m^2 and $m_{56}/m_{28} < 2$	$m_{56} < 1.0$ kg/m^2 note 1
Mod. ASTM C 666-A	n/a	n/a
Pore Protection Ratio	n/a	n/a

Note 1: This requirement may be changed, e.g. to 0.5 kg/m^2. However, the present documentation does not indicate the need for such change.

Exposure Class 3

No recommendations for acceptance criteria for the prescribed frost resistance testing of exposure class 3 can be given, since there is no indications that structures in this exposure class are actually frost susceptible.

However, it must be noted that concrete structures of exposure classes 2 and 3 must be upgraded to exposure class 1, if the structures are impossible to repair, or if the exposure can change during use or deterioration of the structure

2.5 Reservations to the Guidelines

The guidelines to the assessment of frost resistance is based on the research results from the HETEK, Task 2, project. The guidelines are given with the following reservations:

- The materials and results from Task 2 are restricted, hence the guidelines are preliminary.
- The guidelines are valid for portland cement concretes only.
- The frost resistance of certain concrete types, having very low permeability, may not be described by the present guideline

3 Recommendations for Further Research

3.1 Overview of Experience Gained during the Research Period

During the present research project good progress has been made towards formulation of a feasible test strategy for pre-testing and testing of in situ structures in relation to freeze-thaw resistance of concrete.
2 test methods have been suggested and guidelines for specification of acceptance criteria have been prepared.
However, a research programme with time restraints as those given for the present research must necessarily result in recommendations for further research.
Primarily, because the criteria for acceptance cannot be verified by the research as these criteria are in fact an outcome of the research.
Secondly, because a number of reservations to the results, the interpretations and the conclusions have been required.

These are related to:

- Correct classification of the in situ performance of the structure
- Correct classification of the actual environmental exposure
- Correct assessment of equilibrium conditions of the structure with respect to moisture content i.e. frost deterioration
- Assumption that the concrete tested compare with modern, high performance concrete and the cores are representative for the parts of the structure classified in relation to degree of frost resistance
- Relationship between criteria based on frost testing of structures and requirements/criteria to be applied for pre-testing

3.2 Recommendations

Based on the experience gained and results obtained during the research in task 2 of the HETEK project; "Method for testing of frost resistance of high performance concrete" it is recommended that an exploitation of the results of this research is assured through implementation in an extended research verification involving parties from a larger geographical area e.g. the Nordic countries.

The continuation of the research should concentrate on the following main objectives:

1. Documentation and concensus verification of the guidelines for classification of the in situ performance i.e. classification of the degree of frost deterioration

2. Documentation and verification of conformity with European standards (EN 206, EC 2) of the guidelines for classification of the environmental exposure.

3. Formulation of criteria for homogeneity of concrete in a given structure

4. Formulation of a strategy for assessment of "steady state/equilibrium" conditions in a mass of concrete

5. Selection of a large number of suitable concrete structures, characterization/ classification of performance and exposure

6. Assessment of viability of introduction of rapid test methods based on moisture ingress e.g. pore protection ratio

7. Testing to verify criteria for frost resistance of concrete structures

8. Verification through laboratory research that criteria for pre-testing are realistic and assess the economical impact of these criteria

9. Planning of a Nordic/European long term test programme for freeze-thaw testing of concrete.
   The programme shall include production of full scale structures involving at least the following phases:

   i) Pre-testing
   ii) Complete Quality documentation of the structure
   iii) Testing of structures at maturities corresponding to the pre-test conditions
   iv) Monitoring structures

4 Appendices - Test Methods

Appendix 1: HETEK, Task 2: Proposal for Test Method for Determination of Frost Scaling Resistance of Concrete (Modified SS 137245, Borås)

This method follows the Borås Method SS 13 72 45, with only few modifications. Two methods for testing the frost resistance are described. Method A using deicing solution, 3.0 % solution of NaCl, as frost media. Method B using demineralized water as frost media.

Both methods may be used for pre-testing of concrete and for testing of specimens from a concrete structure.

When pre-testing, the concrete has to be cured for 19 days before the test procedure begins.
Upon casting the concrete specimens are stored 1 day in the moulds at 20 ± 2 °C. Then the forms are removed and the specimens are stored in water at 20 ± 2 °C until the test procedure begins.

The modification of the original method relates to curing and shape of the specimens used for pre-testing.

Test Specimens and Conditioning

Pre-testing

Specimens used for the test are usually sawed slices from casted concrete cylinders, diameter 150 mm.
The cylinders should arrive to the testing laboratory at an age of 19 days. Immediately after arrival they must be placed in the conditioning climate.
At 21 ± 1 day 50 ± 2 mm slices are sawed from the concrete cylinders. The slices are taken at least 20 mm from the ends of the cylinders.
(Application of cubical specimens is obtional).

Immediately after sawing the specimens are washed with tapwater, dried with a moist cloth and placed in the conditioning climate. The specimens are placed on the cylindrical side with a distance between each other of at least 50 mm.

Testing of specimens from a structure
When testing specimens from a structure the specimens shall after drilling be washed with tapwater, dried to surface dry condition and wrapped in watertight plastic to prevent moisture exchange with the surrounding air.

When the specimens arrive to the testing laboratory they are placed in the conditioning climate for at least 1 day. When sawing the specimens into slices of 50 ± 2 mm one should avoid reinforcement.

Immediately after sawing the specimens are washed with tapwater, dried with a moist cloth and placed in the conditioning climate. The specimens are placed on the cylindrical side with a distance between each other of at least 50 mm.

Number of specimens
When pre-testing using cylinders with a diameter of 150 mm 5 specimens taken from three cylinders are to be tested. When testing specimens taken from a structure the total exposed area shall be more than 42000 mm^2.

Conditioning related to the test
After sawing into slices the specimens are placed for 7 days in a climate with a temperature of 20 ± 2 °C and 65 ± 5 % RF. During this period all surfaces except for the surface to be exposed are tightened with a watertight material glued to the surfaces. The glue is to be placed all over the surface in an even layer. The edge of the material used shall reach a level of 20 ± 1 mm above the level of the surface to be exposed. To avoid water to penetrate between the material and the side of the specimen a string of e.g. sealant is to be placed in the corner between the water tight material and the surface.

Immediately after the gluing the specimens shall be placed in the conditioning climate. After 7 days demineralized water with a temperature of 20 ± 2 °C is poured to the exposed surface to a height of 3 mm . This moisture exposure shall be maintained for 72 ± 2 hours.

Freeze/Thaw Testing

Method A: Test using deicing Salt Solution, 3.0 % Solution of NaCl
Before testing all surfaces of the specimens except the one to be exposed are insulated with a insulating material with insulating properties as polystyrene cell plast with the thickness of 20 ± 1 mm. Within 15 minutes before the specimens are placed in the freezing cabinet the demineralized water at the exposed surface is exchanged with 3.0 % salt solution of NaCl. The solution shall be maintained to a level of 3 mm hight during the test period. This corresponds to an amount of 53 ml for a cylindric speci-

mens with a diameter of 150 mm. The deicing media shall have a temperature of 20 ± 2 °C when poured on the surface. Then a thin foil of polytene is used for tight protection towards evaporation from the solution. This covering shall be kept horizontal during the test.

In the freezing cabinet the specimens are exposed to repeated freezing and thawing, controlled in such a way that the temperature in the freezing media follows the requirements given in figure 1. The temperature history shall be recorded continuously in the freezing media in the centre of the surface on at least one specimen in the cabinet. This specimen may be a dummy provided the concrete used is of the same quality as the concrete tested.

At the beginning of the test the specimens are placed in the freezing cabinet at the time 0 ± 30 min as shown in figure 1.

The limits of the freeze/thaw curvature are defined as:

Upper limit		Lower limit	
Time, h	Temp. °C	Time, h	Temp. °C
0	24	0	16
5	-2	3	-4
12	-14	12	-20
16	-16	16	-20
18	0	20	0
22	24	24	16

Measures shall be taken providing for the required temperature cycle for all specimens. The distance between the specimens should be at least 50 mm and between the specimens and the walls of the cabinet 50 mm.

After 7, 14, 28, 42 and 56 cycles the following procedure is executed for each specimen during the thawing face between 20 and 24 hours:

- Material which has scaled from the exposed surface is collected individually in a coffee filter. The surface is brushed with a paintbrush and sprayed using a spraying bottle.

- New freezing media is poured to the surface as earlier described.

- The test specimens are placed in the cabinet for further testing.

- The material scaled from the surface is dried to constant weight at 105 $\pm$ 5 °C.

- The total weight is measured with an accuracy of 0.1 g. The dry weight is reported.

For each measurement and each specimens the following is calculated:

M_n / A [kg/m2]

M_n is the the weight in mg of the total scaled material after n cycles

A is the area of the exposed surface in mm^2 .

Method B: Test using Demineralized Water
Method B is identical to method A except for the use of demineralized water as frost media.

Test Results
The test results are given in accordance with section 2.4 Recommendations to Acceptance Criteria.

Reporting
The test report shall inform about:

- the geometry of the specimens, size, surface area, origin, identification

- if known the mix design of the concrete

- the age of the concrete at the time of testing, when relevant reported in terms of maturity

- the composition of the frost media

- the type of testing, execution on casted cylinders as pretesting and on drilled or sawed specimens from a structure or on a concrete product

- for each specimens the amount of scaling material is reported as kg/m^2 corrected to two decimal places. The average, and standard deviation are reported for each test

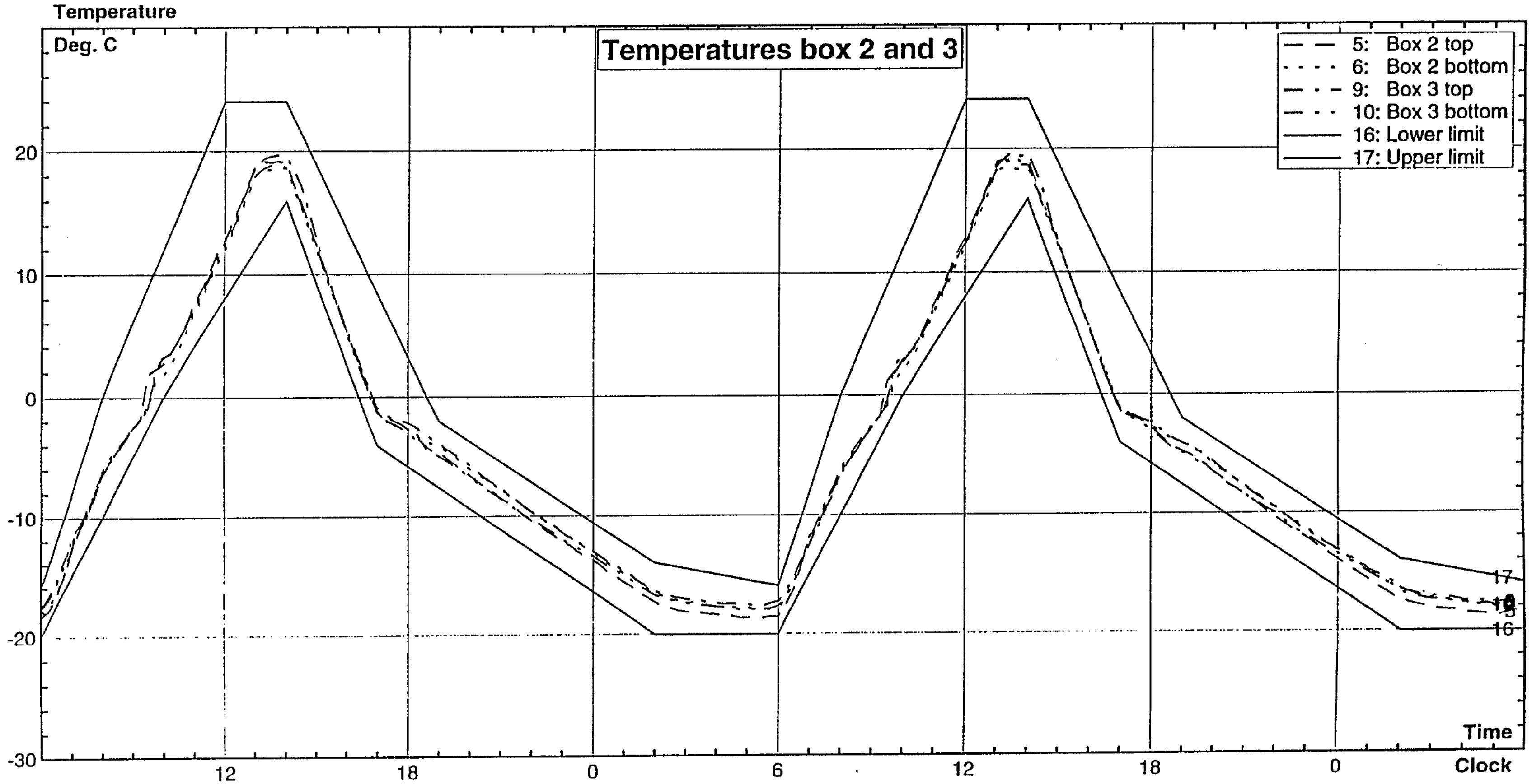
- general information of importance for evaluation of the results, special observation on the specimens e.g. reinforcement, separation. Deviation from the prescribed test procedure.

TMS for Windows
DTI Building Technology

DTI Frost-testing
Connection: E17B

Figure 1

Client: HETEK - Frost	Reference: SS 13 72 44 Boraas	Project: DTI - HETEK	Date: 1997-02-27
Contact: ejp	Initials: jlf	File: aug. - oct.	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 2: HETEK, Task 2: Proposal for Test Method for Determination of Frost Scaling Resistance of Concrete (Modified ASTM C 666-A)

References

ASTM C 666-A: Resistance of concrete to rapid freezing and thawing

ASTM C 490: Standard practice for the use of apparatus for the determination of length change of hardened cement paste, mortar and concrete

Measuring principle

The length change (expansion) of concrete test specimens are taken as a measure of their potential frost resistance.

The deviation from the original test method statement ia related to the length of the specimens only.

Optionally, the reduction of the $E_{modulus}$ of the test specimen may be applied, ref. ASTM C 666-A, this is however not further described in the present test method.

Test Specimens

The test specimens are:

A) cast cylinders (Ø: 100mm x 200 mm) or

B) concrete cores (diameter: 100 mm ±5 mm, Length minimum 200 mm).

The number of test specimens required to assess the frost resistance of a concrete, should be not less than 6. The concrete should have a maturity of not less than 28 M-days when starting the freeze/thaw testing.

A) Cast cylinders.

Test specimens of cast cylinders retain their full length, i.e. 200 mm.

B) Cores.

The test specimens are cores having a diameter of 100±10 mm and a length of minimum 200 mm. In the laboratory the cores are cut to a test specimen length of 150±10 mm.

Test specimens from structures may not dry more than in the structures. Immediately after coring, the samples are thoroughly washed, surface dried with a cloth and wrapped in impervious plastic.

Cores containing casting joints can not be applied for assessing the frost resistance of the concrete. Cores containing more reinforcement bars can not be applied for the testing.

Note: Cores containing single reinforcement bars with a maximum of 12 mm diameter have been tested without any damages correlated to the reinforcement [Eriksen et al. 1997].

At arrival to the lab, the cores are unwrapped, and cut to length. If the outer end of the core is without any defects or notable carbonation, the test specimen can be placed from the exposed surface and inwards. Otherwise the sample must be placed deeper in the core to secure the achievement of an undamaged sample.

During the handling of test specimen 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, subsequent surface drying by use of a damp cloth, and wrapping in impervious plastic

Conditioning

Cast cylinders are water cured at 20°C until testing. If cast cylinders are transported before testing, they shall be wrapped in wet cloth and sealed against drying by impervious plastic. The test specimens must be protected against drying out, during cutting (of cores), mounting of gauge studs, and preparing for testing.

Mounting of gauge studs

The test specimen is mounted with gauge studs centrally in both ends, according to ASTM C 490. The following procedures can be applied:

- The test specimen is placed in a drill stand and in each end of the test specimen, a hole is drilled with the 10 mm diamond core drill using water cooling. The depth of the holes must be 16 mm $\pm$ 2 mm. The central small plug is gently removed. The holes are dried with high pressure air.

- In each hole a gauge stud is mounted, see 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, see 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.

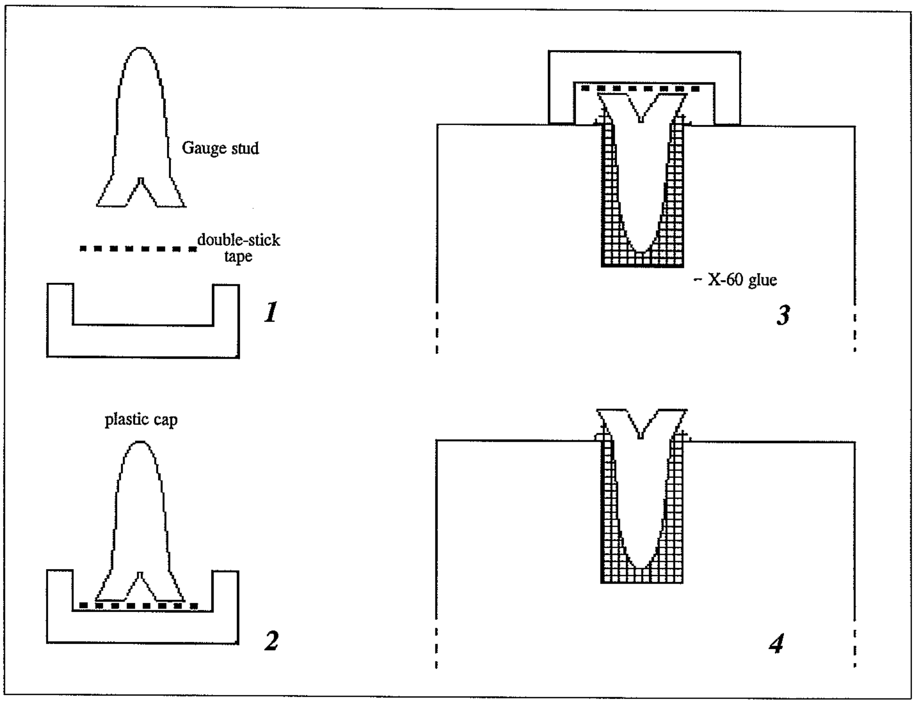


Figure 1 Mounting of gauge stud in the core.

Preparing the Test Specimen For Testing
The specimen must be surrounded by 1-3 mm test liquid during the testing. Furthermore, it must be assured that the freezing of the test liquid cannot cause any damage to the test specimen. Hence, rigid containers cannot be applied.

The following procedures are suggested:

- The top and bottom of the core is covered by a 5-10 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'), see figure 2.

- The test 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 test specimen/spacer net, by surrounding strips of 50 mm broad scotch tape, placed at the bottom, middle and top of the sample. The bottom part of the plastic bag is likewise held tight to the test specimen with scotch tape.

- The wrapped test 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 test 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 test specimen is placed in the F/T-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 test specimen. The test specimen must be fully below the level of frost liquid.

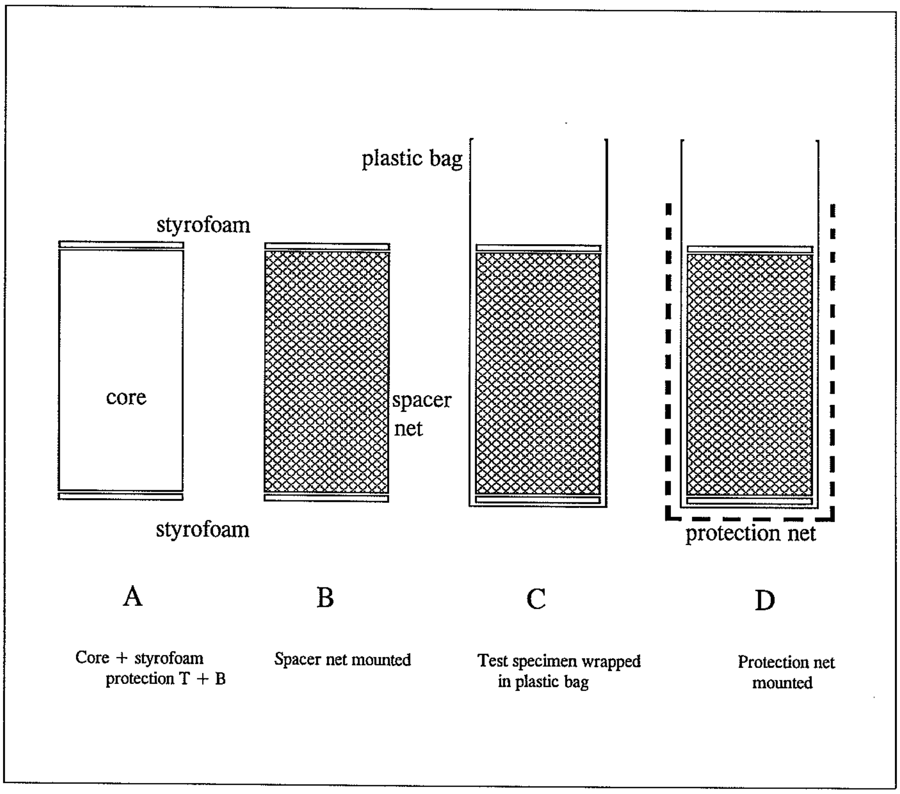


Figure 2 The wrapping procedures for test specimens to be F/T tested.

Freeze/Thaw testing
The freeze/thaw testing is initiated and run for 300 F/T cycles or until the set requirements for expansion is trespassed. After each 36 F/T cycles the length of the test specimens is measured.

The general set-up of the F/T equipment must fulfil the requirements given in ASTM C 666-A, ref. table 1. The following set-up can be suggested:

Automatically, the frost liquid temperature is changed to achieve a central temperature in the test specimens varying from +4.4°C to -17.8°C (both ±1.7°C), within a cycle time of 3.6 hours (±1.6 hours).

The frost liquid ('Antifrogen N') containing F/T-vessel can store as much as 120 test specimens. The Vessel is mounted with an upper steel frame above the frost liquid for fixation of the test specimens. To secure even temperature cycles, the frost liquid is, by pumping, replaced 0.5 times per minutes.

Table 1 Definitions and requirements to the freeze/thaw system.

Parameter	Definition	Requirements
F/T cycle [hours]	Time: T_{max1}-T_{max2}	2 - 5
$Temp_{max}$ [°C]	Maximum temp. measured centrally in concrete dummy	4.4 ±1.7
$Temp_{min}$ [°C]	Minimum temp. as measured centrally in concrete dummy	÷17.8 ±1.7
TP: thawing period [hours]	$T_{min} \rightarrow T_{max}$	TP ≥ ½·VP TP ≥ ¼·Cycle
FP: freezing period [hours]	$T_{max} \rightarrow T_{min}$	FP ≥ ½·KP
HP: heating period [hours]	The heating time of the system (frost liquid vessel)	---
CP: cooling period [hours]	The cooling time of the system (frost liquid vessel)	---
Test specimen size [mm]	Length: L Diameter: D	$L_{cast\ cylinders}$: 200 L_{cores}: 200 (cut to 150) D: 90-110
Test specimen maturity [M-days]	-	(28 M-days for cast test specimens)
Test specimen conditioning	-	Test specimens from structures may not dry more than in the structures.
Test liquid [mm]	Thickness of test liquid layer (tap water)	1-3
End of test	No. of cycles, length change: ΔL,	300 F/T cycles, ΔL ≥ maximum expansion

Measuring the Test specimen Length
The test specimens are measured before start of F/T testing, and subsequently after each 36 F/T cycles, or less, until the testing is terminated.

The length measurements are carried out at a temperature of 20°C. The test specimens must have a constant temperature during the length measurements. The measuring time must be so short that the temperature of the test specimen is not changed.

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

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

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

- The test specimen is placed in the precision dial gauge stand - at each measurement the test 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 test specimen is scrutinized with naked eye and hand lens. All observations, such as crumbling of paste, cracks, pop-outs, general expansion, discolouration a.o. are recorded.

The test specimen is within 5 minutes again wrapped for further testing, test liquid (tap water) is added, and the test specimen returned to the frost liquid containing F/T-vessel.

Test Results
The expansion is computed according to (1):

$$\text{Expansion} = \Delta l / L_0 \times 100\ \% \qquad (1)$$

where
L_0: Test specimen length (in mm) before exposure
l_0: Reading on precision dial gauge (mm with 3 digits) after 0 F/T cycles.
l_i: Reading on precision dial gauge (mm with 3 digits) after i F/T cycles.
Δl: $l_i - l_0$

Reporting
General test report parameters are given. For each set of Test specimens the following parameters are reported for each measure term:

- dial gauge reading for each test specimen,
- computed expansion for each test specimen,
- mean expansion for the set of test specimens,

- visual observations for each test specimen,
- graph depicting the expansion history of each test specimen.

The actually applied time/temperature curve of the testing is enclosed.

Appendix 3: HETEK, Task 2: Proposal for Test Method for Determination of Pore Protection Ratio

References

Vuorinnen, J. (1984): Om skyddsporförhållandet hos betong. DBT publikation nr. 22, Nordisk Workshop Beton & Frost, 1884. Køge.

Measuring principle

The effective air pore volume in a capillary saturated material, in relation to the total pore volume, is determined by weighing under various conditions.

Test Specimens

Test specimens can be cast concrete specimens, e.g. cylinders, or cores from concrete structures. During transport, the samples are not to be dried.

Before testing the sample is by breaking parted in test specimen discs with a thickness of approximately 20-30 mm. The number of test specimens required to assess the pore protection ratio of a concrete, should be not less than 6. The concrete should have a maturity of not less than 28 M-days when starting the test.

Test

The testing includes the following steps:

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

The weighing of test specimens are carried in surface dry condition (wiped with a moist cloth). Weighing must be carried out with 0.01 g precision.

For absorptions are used boiled tap water, cooled to 20°C.

The device for pressure saturation must secure that the prescribed pressure is maintained during the 24 hours test. Hence also adjusted during the water filling of the air pores.

The weight measurements after 24 hours pressure must be taken immediately after pressure release.

Test Results
The pore protection ratio is calculated according to (1):

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

where:

m_{capp}:	is the sample weight at constant weight, after approximately 400 hours of capillary saturation.
m_{press}:	is the sample weight after 24 hours of water saturation in pressure of 15 MPa.
m105:	is the sample weight after drying at 105°C.

Reporting
General test report parameters are given. For each test specimens the following parameters are reported:

- all weighing results
- pore protection ratio for each slice
- mean pore protection ratio for the set of test specimens

Furthermore, a graphical depiction of the absorption against square root of time are presented for further evaluation of the testing.