Frost damage on concrete assessment of the current state of the structure

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Frost damage on concrete
Assessment of the current state of the structure

A contribution to the BRITE/EURAM project
BREU-CT92-0591
"The Residual Service Life of Concrete Structures"

Göran Fagerlund

Report TVBM-7078
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Contents

Preface

This report is part of the BRITE/EURAM project BREU-CT92-0591 "The Residual Service Life of of Concrete Structures". Six partners are participating in the project:

1: British Cement Association, U.K. (The Coordinator)
2: Instituto Eduardo Torroja, Spain
3: Geocisa, Spain
4: The Swedish Cement and Concrete Research Institute, Sweden
5: Cementa AB, Sweden
6: Division of Building Materials, Lund University, Sweden

Three deterioration mechanisms are treated:

1: Corrosion of reinforcement
2: Freeze-thaw action[1]
3: Alkali-silica reaction

This report deals with freeze/thaw, and it refers to Task 2, "Assessment of the current state of the structure". In the report, test methods that can be used for the following types of assessment are described:

1: Methods used for an assessment of the residual strength of the structure.
2: Methods used for an estimation of the future frost destruction.
3: Methods used for a characterization of the moisture state of the structure.

Lund June 1995

Göran Fagerlund

[1]) At the end of the report, is a list of all reports produced within task 2, "Freeze-thaw action".

I: In-situ investigation of the structure

In the following, the exact number of specimens for each test, or the location where to drill out specimens, is not considered. It will be individual for each structure, and must be determined by the experienced investigator.

1. The mechanical properties of the concrete

Aim:

1: To make possible a quantitative determination of the actual degree of frost damage of the concrete as a material (loss in compressive strength, loss in tensile strength, loss in bond, loss in E-modulus)[2]

2: To make possible an assessment of the current structural stability[3]

3: To make possible an extrapolation of the future degradation of the structural stability [4]

Test methods

Strength and E-modulus:

Traditional test methods, practised to drilled out cores, are used

Bond strength:

The residual bond strength is evaluated from the residual strength, according to relations presented in Deliverable 28.1 to the BRITE/EURAM project; [1].

[2]) Knowledge of the degree of damage is required as an important input for an extrapolation of the future degradation; See [11].

[3]) Traditional methods are used for translating mechanical properties to structural stability. Consideration must be taken to surface scaling, to loss of bond and anchoring capacity, and to synergetic effects caused by other destruction mechanisms, acting simultaneously; such as alkali-silica reaction and reinforcement corrosion.

[4]) Methods for predicting the future degradation of the concrete strength, bond and E-modulus are described in [11].

2. The visual appearance - scaling and cracking:

Aim:
To find proof of the existence of frost damage, and the extent of this. Such proofs are:

1: Surface scaling due to salt/frost attack[5]

2: Internal cracking and loss of cohesion[6]

Test methods:
Surface scaling :
Surface scaling is measured in-situ, by some sort of gauge, such as a measuring clock mounted on a bar. The scaling depth is counted from a reference initial surface, that can sometimes be difficult to define. One might use unscaled parts of the structure, or one might base the measurements on the initial drawings used at the construction phase.

The scaling front will not be perfectly smooth. The actual profile is determined. The reinforcement bars shall be located by a cover-meter, and the residual cover shall be determined. This is important for an assessment of the anchoring capacity of the reinforcement bars and, consequently, for the structural stability. It is also important for an assessment of the residual service life with regard to reinforcement corrosion.[5]

Internal damage:
Traditional techniques are used, such as visual analyses of thin-sections, petrographical analyses etc. By an analysis of the crack pattern, an experienced petrographer ought to be able to see whether the damage is due to frost attack, or to any other types of internal attack, such as alkali-silica reaction, secondary cement reactions, sulfate attack, etc. The techniques are not described here.

Salt deposits and crystals in the air-pore system is quantified. It gives information of the amount of the inactivated air-pore volume.[7]

[5]) The current depth of salt scaling is an important input for an assessment of the future scaling; see [11]. It is also required for an assessment of the penetration of chlorides and/or carbonation. This synergy between scaling and reinforcement corrosion is described in [2].

[6]) It is used as an indicium, that it is frost attack that has taken place, and not another type of attack. This is important for the prediction of future deterioration.

[7]) An air-pore, that is filled with secondary cement reaction products, or with calcite, is not an active air-pore. Evidently, it can be filled with water, which is a prerqusite for the nucleation of crystals. Besides, a completely filled air-pore is not functioning as a recipient for water, that is displaced during freezing.

3: The air-pore structure

Aim:
To determine the "quality" of the air-pore structure, expressed in terms of the following parameters:[8]

1: The total air content

2: The specific area of the air-pore system

3: The spacing factor of the entire air-pore system

4: The size distribution of air-pores

Test method:
Theoretical background:
The theoretical principles behind the determination of the air-content, the specific area and the spacing factor is based on the so-called *linear traverse method* described in ASTM C457. By adding the *Lord-Willis method* for analyzing chord intercepts, the pore-size distribution is also obtained by the same experimental technique; [3].

Practical methods:
The test can be made by watching the air-pore calotte distribution of polished, bigger samples. The air-pores can, either be observed by the manual method, as it is described in ASTM C457, or the observation can be made by a TV-camera mounted on a microscope, and coupled to an automatic image processing system. Even in the latter case, the software is based on the theoretical background behind the linear traverse method, described in ASTM C457.

The test can also be made on smaller thin-sections. In this case, many sections are needed in order to obtain the necessary precision. The diameter distribution of the air-pore calottes is measured. A mathematical transformation of the observed diameter distribution is required, in order to find those air-pore parameters that are based on the linear traverse measurement. If this transformation is not made in the correct way, the spacing factor will not be the same in the two methods.

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[8]) Information of the air-pore system can be used for a quantitative estimation of the potential frost resistance, and for an assessment of the so-called potential service life with regard to frost; see Deliverables 12.5 and 18.6 to the BRITE/EURAM project; [4], [5].

4. The effective air-pore volume

Aim:
Only air-pores that stay air-filled in the practical situation will function as stress relievers during the freezing process. Air-pores can become inactivated due to water-uptake. This occurs when the pores are inter-connected, so that they form continuous channels. It also occurs when the pores are so small that they take up water due to air-dissolution.[9, 10]

The effective air-pore volume gives information of the potential frost resistance. It is also a fundamental parameter for a theoretical service life analysis. [11]

Test method:
Cores with diameter 10 to 15 cm are drilled out of the structure. 20 to 25 mm thick slices are cut from the cores. The slices are treated in the following way:

1: Pre-drying in room-climate, protected from carbonation, during at least 2 weeks.

2: Weighing immediately before the suction test. Weight Q_o.

3: Placing in a tray containing water. Only 1-2 mm of the thickness is immersed.

4: Taking up and weighing at different time intervals; 10, 20, 30 minutes, 1, 2, 4, 6 hours, 1, 2, 3 ,4 ,5 etc days, until about 28 days. Before weighing, the bottom surface is wiped with a moist sponge. Directly after weighing, the specimen is once again placed in the tray. This is covered by an impermeable lid (e.g. Plexiglass). The weights are called Q_t.

5: After terminated water uptake, the specimens are dried at +105°C to equilibrium and weighed, Q_{dry}.

6: Vacuum-filling by pre-evacuation at max 2 torr during at least 24 hours, followed by water uptake with the pump running for about 1 hour, and finally water storage at ordinary atmospheric pressure during at least 1 week. Weighing in air and immersed in water, $Q_{sat,a}$ and $Q_{sat,w}$.

7: Calculating the degree of saturation S_{CAP} versus the square-root of time. Degree of saturation is defined:

$$S_{CAP} = \text{total water/total porosity} = (Q_t - Q_{dry})/(Q_{sat,a} - Q_{dry}) \qquad (1)$$

[9]) This process is described in Deliverable 12.5 to the BRITE/EURAM project; [4].

[10]) Air-pores can also be filled with salt crystals. This is seen in the petrographical analysis described above.

[11]) See Deliverables 12.5 and 18.6 to the BRITE/EURAM project; [4], [5].

8: Defining the nick-point on the absorption curve (see the illustration below), where the early rapid absorption goes over to a slow absorption. This nick-point absorption is called Q_n, or in terms of degree of saturation, $S_{CAP,n}$

9: Calculating the total porosity P:

$$P = (Q_{sat,a} - Q_{dry})/(Q_{sat,a} - Q_{sat,w}) \quad (2)$$

10: Calculating the effective air content a_{eff}. This is defined:

$$a_{eff} = (1 - S_{CAP,n}) \cdot P \quad (3)$$

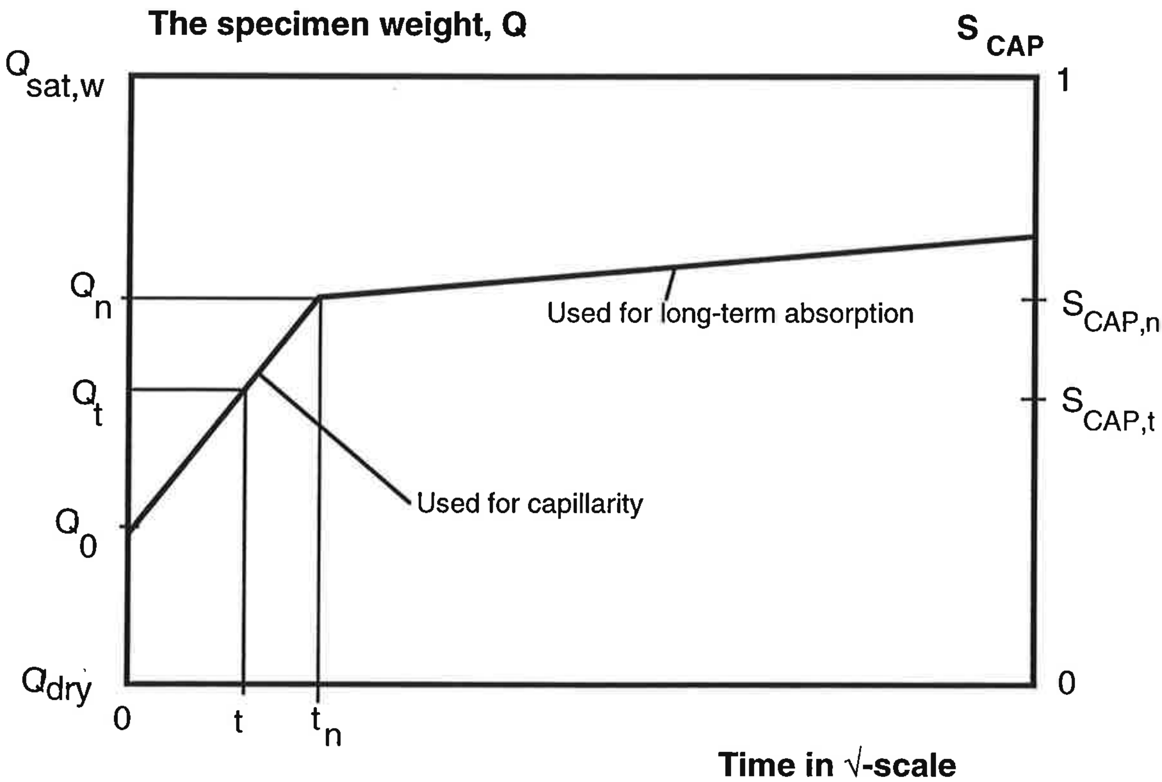


Illustration showing the result of a water absorption test used for determination of the effective air content, the capillarity, and the long-term absorption.

5. The capillarity and the long-term water absorption

Aim:

1: The capillarity gives information of the speed by which the concrete responds to exposure to free water. Two types of data are obtained:

a: *The absorption coefficient* telling the rate of water absorption. The value depends on the water content when suction starts.The absorption coefficient can be used for calculations of the time-moisture fields in the concrete surface, and, therefore, it is important for the prediction of the service life with regard to reinforcement corrosion.[12] It is of less importance for analysing frost resistance.

[12]) Examples of such calculations are given in Deliverable 12.1 to the BRITE/EURAM project; [6].

b: *The resistance coefficient* telling the rate by which the water front penetrates the concrete. It is sensitive to inner damage. For an undamaged concrete, the value shall be within the range $5 \cdot 10^6$ to 10^8 s/m^2. Lower values are signs of inner damage.

2: The long-term absorption gives information of the potential service life, and can be used for a prediction of the potential service life. [13]

Test method:
The same test method, as that used for determination of the effective air content, is used; see the illustration above. The procedure is as follows.

Capillarity:
The absorption coefficient, k (kg/(m$^2 \cdot$s$^{1/2}$), is defined by the slope of the *first part* of the absorption-square-root of time curve; from time zero until the nick-point. This slope can be obtained by linear regression. The following definition is valid:[14]

$$k = \frac{dQ}{d(t^{1/2})} \cdot \frac{1}{A} \qquad (4)$$

Where, $dQ/d(t^{1/2})$ is the slope of the water absorption curve, and A is the cross section of the specimen.

The result depends on the initial water content, expressed in terms of the initial weight Q_o; the lower the water content, the higer the absorption coefficient.

From the test, the so-called resistance coefficient, m (s/m^2), can be determined. It is defined:

$$t = m \cdot z^2 \qquad (5)$$

Where t is the suction time, and z is the depth of penetration of the moisture front. Thus, m is a measure of the resistance offered by the concrete to moisture penetration. m is much less dependent of the initial moisture content than k.

The value of m is obtained from the nick-point absorption:

$$m = t_n/H^2 \qquad (6)$$

Where, t_n is the nick-point time, and H is the thickness of the specimen.

[13]) The theory is described in Deliverable 12.5 to the BRITE/EURAM project; [4]. An application of the theory to a practical assessment is described in [11].

[14]) It might be that the absorption curve does not completely follow a square-root relationship. It might also be that the absorption curve is non-linear in a square-root time-scale. A typical case is when the initial water content is very high. In such a case, a new test with lower water contents can be made. One can also normally find a certain portion of the curve for which the definition of k can be applied.

Long-term water absorption:
This is determined from the second part of the absorption curve; after the nick-point has been obtained.

The following expression is determined by linear regression:

$$S_{CAP,t} = A + B \cdot t^{C} \tag{7}$$

Where, $S_{CAP,t}$ is the capillary degree of saturation after time t. It is calculated from the experimental points by the method that was described in the test method for the effective air content. A,B and C are coefficients found by the regression analysis. [A≈ $S_{CAP,n}$ (the nick-point degree of saturation).]

6. The potential frost resistance

Aim:
1: To obtain information of the general level of frost resistance of the concrete

2: To make possible an estimation of the potential residual service life of a structure that is susceptible to be frost damaged, but that is not yet damaged. [15]

Test methods:
One can distinguish between methods that yield qualitative information only, and methods that yield quantitative information concerning service life.

Qualitative test methods:
In these methods, the specimen is exposed to repeated freeze/thaw cycles in a manner, that is not always representative of the practical situation. One obtains information of the general level of frost resistance, but not of the frost resistance in the real case. The information obtained is often expressed in terms of judgements such as:
* Excellent frost resistance
* Good ....
* Fair ....
* Average ....
* Poor ...

There are many test methods to select between. The most widely used method is the American ASTM C666. This is a rapid freezing and thawing in water, or in water and air. Damage is measured by the loss in fundamental frequency of transverse vibration (a function of the loss in the E-modulus, and the weight loss). Also the scaling, and the length change can be measured. There are two variants of the method:

Procedure A. "Rapid water". In this, the specimen is constantly stored in water during all the 300 cycles that are specified.

Procedure B. "Rapid air". In this, freezing is made in air, but thawing in water.

[15]) Situations, when such an assessment is suitable, and how it is made, is shown in [11].

It seems reasonable to use Procedure A for structures, that are used in very wet environments, and Procedure B for more dry structures. It must be noted, that small changes in the test procedure, give big changes in the observed behaviour. [16]

The test is performed on drilled out specimens

Quantitative test metod:
Information of the potential service life can be obtained by the so-called "Critical Degree of Saturation Method", which is a Tentative RILEM-method. [17]

The principles of the method are as follows (see the illustration below):

1: The critical degree of saturation, S_{CR}, is determined by a freeze/thaw test. This can be performed as a multi-cycle freeze thaw on many specimens at the same time, or as a single freeze/thaw experiment, with one specimen.

2: The long-term capillary degree of saturation, S_{CAP}, is determined by the method described for determination of the effective air content. Three constants are determined for the long-term water absorption, A, B, C. The capillary degree of saturation is defined by:

$$S_{CAP,t} = A + B \cdot t^C \qquad (8)$$

Then , the potential service life, t_{pot}, is calculated by:

$$t_{pot} = \{(S_{CR} - A)/B\}^{1/C} \qquad (9)$$

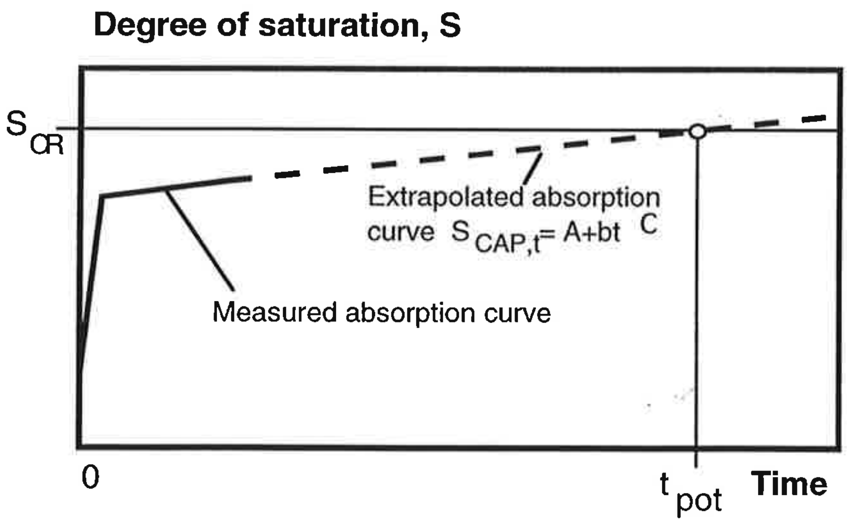


Illustration showing the definition of the potential service life

[16]) The methods are also described in Deliverable 30.4 Part 1 to the BRITE/EURAM project; [7].

[17]) The test procedure is described in [8]. Suitable situations, when this method might be used for prediction of the future degradation, are presented in [11].

7. The potential (salt) scaling resistance

Aim:
1: To find the general level of the scaling resistance of the concrete

2: To find the salt scaling resistance of a concrete, that has not been exposed to salts in the past, but migth be so in the future

3: To find the scaling resistance of a concrete, that has been exposed to salts in the past, but will not be so in the future

Test method:
The method, most widely used, is the Swedish test method SS 13 72 44. In this, cast specimens, or cores, are exposed to, either 3% NaCl-solution, or pure water. Each freeze/thaw cycle has a duration of 24 hours. In total 56 to 112 cycles are performed. Useful information is, however, obtained already after the first cycles.

In the actual case, drilled out cores shall be used. The diameter shall be at least 10 cm and preferably 15 cm. The length shall be at least 10 cm.The surface, exposed in the test, shall be the real outer surface of the core.

For a concrete, that is exposed to de-icing salts in practice, a 3% NaCl-solution shall be used as freeze/thaw medium. For a concrete, that is not exposed to any salts,pure water shall be used. For a concrete in sea water, this might be used in the test. [18]

8. The level of free moisture

Aim:
The aim is to find the actual degree of saturation of the concrete, S_{ACT}. By comparing this with the capillary degree of saturation, $S_{CAP,t}$, or with the nick-point degree of saturation, S_n, obtained in a capillary absorption experiment, one can estimate the risk of frost damage, and the observed behaviour of the structure can get an explanation.[19]

Test method:
The best method is to take out cores from the structure. This must be done without adding moisture, and without drying out moisture. A possible method is to drill small holes in a circle with about 15 cm diameter, and break loose the "core". This must be sealed immediately, in order to protect it from moisture changes. The core is treated in the following way:

[18])Suitable situations, when this method might be used for prediction of the future degradation, are presented in [11].

[19]) The information is also of great interest for an assessment of alkali-silica reaction.

1: The core is weighed in its natural moisture condition, Q_w

2: The core is dried at +105°C until equilibrium, and weighed, Q_{dry}.

3: The core is vacuum-saturated by the technique described for the effective air content, and is weighed in air, $Q_{sat,a}$.

4: The degree of saturation $S_{cap,w}$ is obtained by:[20]

$$S_{CAP,w} = (Q_w - Q_{dry})/(Q_{sat,a} - Q_{dry}) \tag{10}$$

Cores shll be taken at different places, and at different climatic conditions.

9. The relative humidity

Aim:
The aim is to get general information of the moisture level of the structure. This information is, however, more important for an assessment of reinforcement corrosion, than for an assessment of frost damage.

Test mehod:
The test shall be made with RH-sensors, that are carefully calibrated, and with a deviation from the true value of less than ±2% in RH.

The measurements can be made in three ways; see the illustration:[21]

1: In drilled holes, in-situ on the structure. The hole is lined with a plastic tube. The space between the tube and the concrete is sealed. Moisture is only allowed to enter the hole at its bottom end. The RH-probe must be designed in such a way, that a small space can be enclosed at the end of the tube, in which the gauge can be located. Holes are drilled to different depths, so that the RH-profile can be obtained.

2: In drilled holes without lining. Then, the space between the probe and the hole must be sealed. The measurement depth is less well-defined than in method 1.

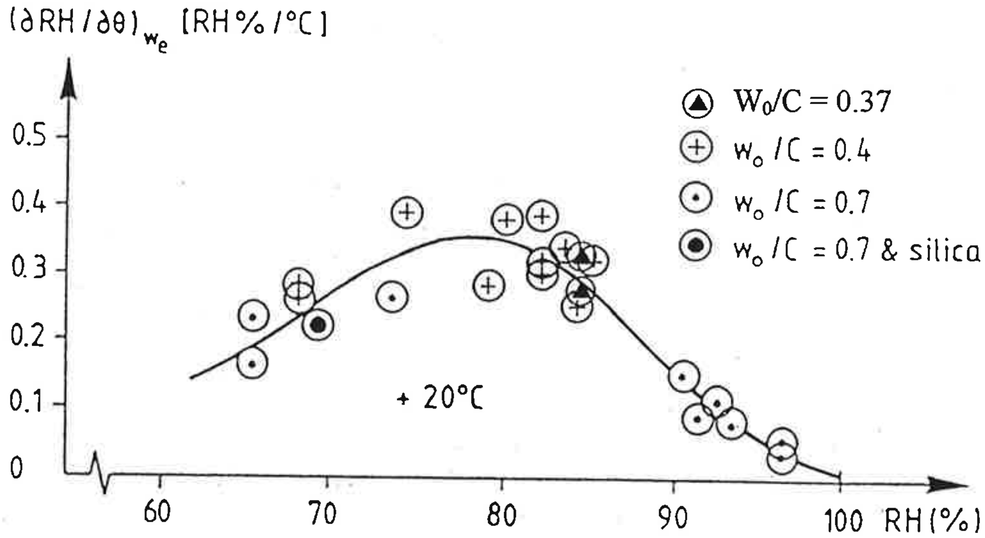
3: At the laboratory, in test tubes containing pieces of the concrete taken from the structure. The pieces are taken out of the structure not using moisture. The same technique as for determination of free moisture can be used. Pieces are taken from different depths, so that the moisture profile can be obtained. Moisture is measured by the RH-probe inserted in the test tube.

[20]) If this is higher than the nick-point absorption, there is an imminent risk of frost damage.

[21]) The technique for RH-measurement and its precision, and techniques for calibration of the gauges, are described in [9]

Reliable results can only be obtained after a certain measurement time. The reason is, that it takes time for moisture to leave the concrete, and bring the surrounding air into equilibrium. Normally, 24 hours is sufficient. The RH-sensors must be calibrated, both before and after the measurement. It is also important that the sensor is pre-conditioned at a RH, that is lower than that of the structure. The sensors often has a significant hysteresis; i.e. the same RH gives a different signal if the sensor is on its desorption curve, than if it is on its adsorption curve.

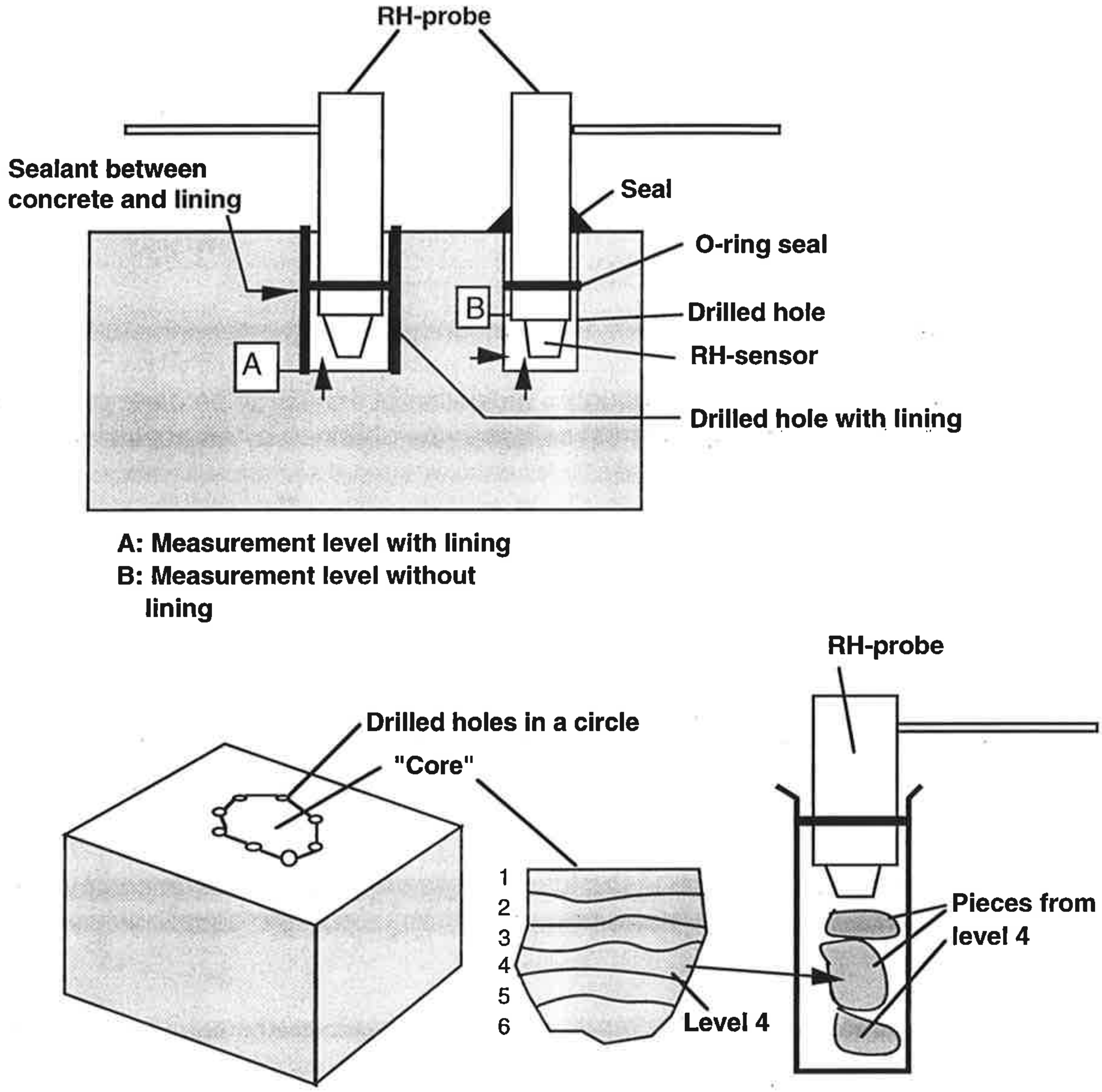
Compensation must be made for temperature. If the temperature is higher at the measurement than in the structure (this is often the case when the measurement is made in the laboratory), the RH-value observed will be some percentage higher than the real value. The reason is that the equilibrium moisture curve (the sorption isotherms) of concrete is depending on the temperature; the lower the temperature, the higher the equilibrium moisture content. A diagram for this adjustment is shown in the figure below. The correction is maximum at about 80% RH. At this RH-level, the measured temperature shall be corrected by about 0,4% in RH, for each degree of temperature difference between the structure and the laboratory. [22]



Change in RH for a certain change in temperature, $\delta RH/\delta\theta$, assuming the total internal moisture content, w_e, being constant. The average temperature is +20°C. The figure expresses the influence of temperature on the sorption isotherms[23]

[22]) The correction is important which is shown by the following example: The temperature of the structure is +10°C. The temperature in the laboratory, where the RH-measurement is made, is +22°C. The measured RH-value is 80%. Then, the real RH in the structure is 80-12·0,4 = 75%. The correction is big, and will have a significant influence on the estimated corrosion rate. The temperature effect also implies that RH inside a concrete will change when the temperature of the structure is rapidly changed; viz. the response of a concrete to temperature changes is normally so rapid, that the concrete has not time to come to a new moisture equilibrium. Slow seasonal temperature changes will not have the same effect. Then, the concrete has time to come to the new moisture equlibrium.

[23]) The curve is taken from [10]:



Different techniques for measuring RH

II: Characterization of the micro- and macro-climate outside the structure

It is important, for an evaluation of the future degradation, to have some information of the surrounding climate. Important parameters for frost attack are:

1: Access to free water; amount of precipitation, water splash, ponding in lower parts of the structure, etc

2: Minimum freezing temperatures and frequency of low freezing temperatures[24]

3: Use of salts; duration and amount[25]. Indication of salt spray on parts of the structure, not directly exposed to salts, can be obtained by an analysis of the chloride profile in the concrete.

4: Exposure to sea water [26]

III: Estimation of the initial quality, and the expected quality, had no degradation taken place

It is important for a prediction of the future degradation, that the present level of damage can be estimated. This information is required in the equations used for prediction. [27]

The initial quality, expressed in terms of strength and E-modulus, can be obtained in at least three ways:

1: Indirectly, from tests made during the production phase

2: Indirectly, from calculations based on the mix design

3: Directly, from tests of cores taken from undamaged parts of the structure

The expected current quality, had no damage taken place, can be assessed from 1: and 2: above by traditional methods for calculating long-term strength growth, taking time and moisture into consideration.

[24]) Required for design of a scaling test.

[25]) Ditto

[26]) Ditto

[27]) These equations are given in Deliverable 30.4 Part 3 to the BRITE/EURAM project; [11].

References

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List of reports within Task 2, "Freeze-Thaw"[28]

All reports are prepared by the present author, except Deliverable 12.1, which is prepared by the present author in collaboration with Göran Hedenblad.

All reports are published during the period 1993-1995.

* **Deliverable 12.1:**	Calculation of the moisture-time fields in concrete.
* **Deliverable 12.5:**	The long-time water absorption in the air-pore structure of concrete
* **Deliverable 18.6:**	The critical spacing factor
* **Deliverable 24.2:**	Influence of environmental factors on the frost resistance of concrete
* **Deliverable 28.1:**	Effect of frost damage on the bond between reinforcement and concrete
* **Deliverable 30.1:**	Frost Damage on concrete. Assessment of the current state of the structure. (The present report)
* **Deliverable 30.4 Part 1:**	Freeze-thaw resistance of concrete. A survey of destruction mechanisms, technological factors, test methods
* **Deliverable 30.4 Part 2:**	Interrelations between the service life, and the air content of concrete exposed to freeze-thaw
* **Deliverable 30.4 Part 3:**	Frost damage on concrete. Estimation of the future deterioration

[28]) A large number of reports have also been produced within the two other tasks, "Corrosion of Reinforcement", and "Alkali Silica Reaction". The whole project will be summed up in a manual.