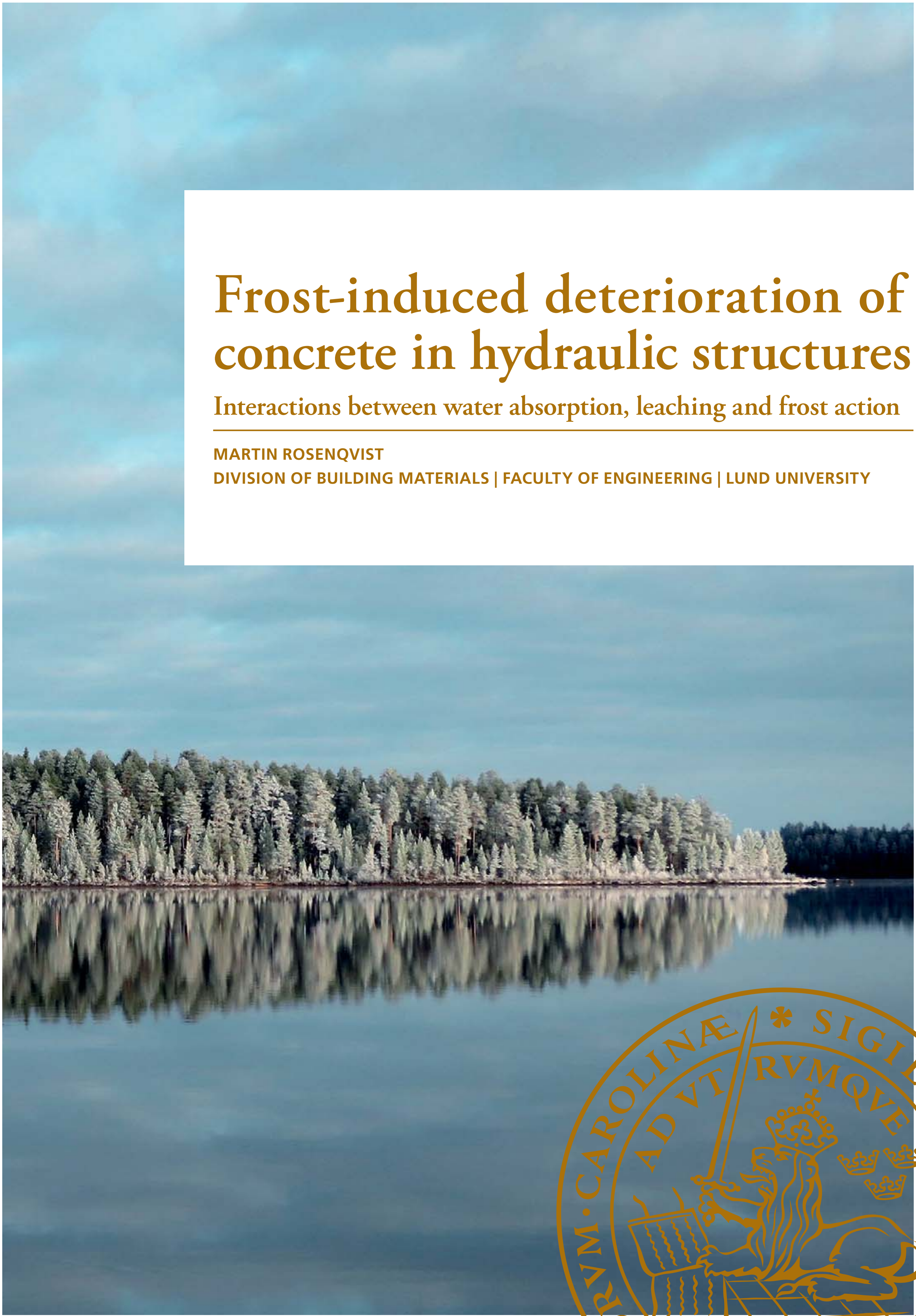
Frost-induced deterioration of concrete in hydraulic structures

Interactions between water absorption, leaching and frost action

MARTIN ROSENQVIST
DIVISION OF BUILDING MATERIALS | FACULTY OF ENGINEERING | LUND UNIVERSITY



Erratum

This erratum sheet is issued to provide additional information to the Preface for the doctoral thesis of Martin Rosenqvist, titled *Frost-induced deterioration of concrete in hydraulic structures: Interactions between water absorption, leaching and frost action*, Lund University, 2016, ISBN 978-91-7623-900-1 (print) and 978-91-7623-901-8 (pdf):

- Add the following sentence after the last sentence of the first paragraph of the Preface on page III: “Kyösti Tuutti and Skanska AB are acknowledged for their support during the application process prior to the start of this work”.

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Preface

The research leading to this thesis was carried out at the Division of Building Materials at Lund University and at the Vattenfall Research and Development Laboratories in Älvkarleby. The work was jointly funded by Energiforsk AB (Swedish Energy Research Centre), SBUF (The Development Fund of the Swedish Construction Industry) and SVC (Swedish Hydro Power Centre), to whom I am very grateful. I also want to thank Holger Ecke and Vattenfall AB for giving me the opportunity to undertake part-time postgraduate studies.

The success of the work presented in this thesis could not have been possible without the support and assistance of many people. First of all, I would like to thank my supervisors Lars Wadsö, Katja Fridh and Manouchehr Hassanzadeh for providing me with their expertise, experience and enthusiasm. I also want to thank Göran Fagerlund for writing the research proposal and for valuable discussions.

Furthermore, I want to thank my colleagues at the Division of Building Materials in Lund and at the Civil Engineering group in Älvkarleby for their support and advice over the past years. Special thanks go to my friend and colleague Mikael Oxfall for all his support throughout the years. I also want to thank Christian Stein for spending two months in Älvkarleby helping me out in the laboratory.

Carl-Oscar Nilsson and Stefan Norberg are gratefully acknowledged for giving me the opportunity to take concrete cylinders from existing concrete dams. Special thanks go to Alexandra Bertron for inviting me to collaborate on the analysis of the concrete cylinders at the Laboratoire Matériaux et Durabilité des Constructions at Université Toulouse III - Paul Sabatier.

I also want to express my gratitude to my parents and the rest of my family for believing in me. Finally, I am very grateful to Anna for her support, understanding, encouragement and love which have kept me motivated throughout this long and at times difficult process.

Lund, September 2016

Martin Rosenqvist

Summary

Frost deterioration of concrete can result in severe consequences to the safety, durability and functionality of a structure since it impairs the strength of the concrete. Frost damage may occur to structures that are in contact with water and subjected to frost action. Different types of concrete damage, which are suspected to be frost related, have been observed in concrete structures in Swedish hydro power plants. Questions have consequently been raised regarding the durability of concrete in hydraulic structures in cold climates. “Hydraulic structure” is the umbrella term for structures in contact with water – hydro power stations, dams, locks, canals, harbours and bridge piles.

Different types of suspected frost related damage to concrete structures in hydro power plants are identified and categorised in this thesis. The underlying causes of damage are experimentally investigated by means of laboratory and field studies. Knowledge about the deterioration of concrete is important in order to secure long service life for hydraulic structures. The obtained results can be used as input for repairs of existing structures and in the case of new builds. The results may also be applicable to hydraulic structures in other countries where similar environmental conditions are present.

The environmental exposure conditions of most Swedish hydraulic structures can be considered harsh. Most hydraulic structures are in contact with water all year round and are subjected to frost action in winter. The water in Swedish rivers is generally considered soft due to the geology of Sweden. Ice floes and driftwood may also cause abrasive wear to some structures. Progressive deterioration of the concrete surface occurs at the waterline of many hydraulic structures. Despite the fact that these structures are exposed to fresh water, the damage is similar in appearance to salt scaling of concrete. Surface deterioration results in exposure of the coarse aggregate and eventually the reinforcing steel.

Analysis of the chemical composition of the cement paste shows that long-term exposure to soft water causes leaching of the concrete surface. Leaching leads to a decrease in the resistance against frost action and abrasion. The surface of frost resistant concrete may also suffer from frost damage if subjected to leaching prior to freezing. This thesis experimentally demonstrates that different degradation mechanisms can boost each other since the amount of superficial damage caused by the combined effects of leaching, frost action and abrasion exceeded the total amount of damage separately caused by these mechanisms.

Progressive deterioration of the concrete surface at the waterline begins with leaching during the spring, summer and autumn months. Hence, the concrete surface becomes susceptible to frost action and is damaged in winter. During the spring, the damaged surface layer falls off and the process begins again.

In some cases, internal damage has been observed at and just above the waterline of hydro power structures built prior to the 1950s. Experimental results show that internal frost damage may occur above the waterline in non-frost resistant concrete. Determination of saturation levels in concrete in existing structures and in specimens after laboratory tests showed that the risk of internal frost damage at and above the waterline is low in frost resistant concrete.

Another type of internal damage has been observed far below the waterline of thin water retaining concrete structures. The damage can be characterised by spalling of large concrete pieces. All damaged structures were subjected to long periods of unidirectional freezing in winter. The studies performed show that poor concrete quality and the effects of ageing and imperfections in the concrete may facilitate growth of macroscopic ice lenses, which causes spalling.

In mechanically sound concrete with a water to cement ratio (w/c) lower than 0.9, the risk of macroscopic ice lens growth is low. In concrete with internal cracking due to frost damage, spalling may occur within a few days regardless of the w/c-ratio. Concrete spalling may occur also in concrete with cavities and other imperfections. However, the higher the quality of concrete, the longer the freezing time required to facilitate macroscopic ice lens growth. Since unfavourable temperature and saturation conditions may exist in winter, the risk of macroscopic ice lens growth in thin water retaining concrete structures cannot be overlooked.

Determination of saturation levels in concrete from a 55-year old dam showed that high saturation levels are to be expected so that even frost resistant concrete is at risk of frost damage. Microstructural observations of concrete from the dam further showed that the frost resistance of concrete can be reduced due to the fact that air voids fill with ettringite and calcium hydroxide crystals over time. In spite of high saturation levels in the concrete, the risk of frost damage can be minimised by preventing thin water retaining structures from freezing in winter.

Keywords: Hydraulic structures, Dams, Concrete, Cement, Water absorption, Degree of saturation, Deterioration, Frost resistance, Spalling, Macroscopic ice lens growth, Leaching, Synergy

Sammanfattning

Frostnedbrytning av betong kan få allvarliga konsekvenser för en konstruktions säkerhet, beständighet och funktionsduglighet eftersom betongens hållfasthet försämras. Frostskador uppstår vanligtvis i konstruktioner med hög fuktbelastning och som periodvis utsätts för frostangrepp. Olika typer av betongskador, vilka kan misstänkas vara frostrelaterade, har påträffats i svenska vattenkraftsanläggningar. Följaktligen har frågor väckts kring betongens beständighet i vattenbyggnader i kalla klimat. Vattenbyggnader är ett samlingsnamn för konstruktioner i anslutning till vatten - vattenkraftstationer, dammar, slussar, kanaler, hamnar och bropelare.

I föreliggande avhandling har olika typer av misstänkta frostrelaterade skador i svenska vattenkraftverk identifierats och kategoriserats. De bakomliggande orsakerna har undersökts experimentellt genom laboratorie- och fältstudier. Kunskap om betongens nedbrytning är viktig i syfte att säkerställa och möjliggöra lång livslängd för vattenbyggnader. Erhållna resultat kan användas som underlag dels vid reparation av befintliga konstruktioner samt dels vid om- och nybyggnationer. Erhållna slutsatser från de olika studierna bedöms även vara tillämpbara för vattenbyggnader i andra länder med liknande förhållanden.

Miljöförhållandena vid de flesta vattenbyggnader i Sverige kan antas vara hårda. Många vattenbyggnader står i kontakt med vatten året om, samt utsätts för frostangrepp vintertid. Vattnet i svenska sjöar och vattendrag kan generellt klassas som mjukt till följd av de geologiska förutsättningarna i Sverige. Dessutom kan is och övrigt drivgods orsaka nötningsrelaterade skador på vissa konstruktioner.

Successiv nedbrytning av betongens yta längs vattenlinjen sker på de flesta vattenbyggnader. Skadorna påminner om avskalning orsakad tösalter trots att konstruktionerna står i kontakt med sötvatten. Nedbrytningen av betongytan leder till friläggandet av grövre ballastkorn, samt i förlängningen även armeringsjärn.

Genom bestämning av cementpastans kemiska samansättning har det visats att långvarig kontakt med mjukt vatten orsakar urlakning av det yttre betongskiktet. Urlakningen leder i sin tur till att ytans beständighet gentemot frost och nötning försämras. Även betong som anses vara frostbeständig uppvisar frostskador om ytan urlakas innan frostangreppet inträffar. Att olika nedbrytningsmekanismer kan förstärka varandras effekter bekräftades experimentellt genom att samverkan mellan urlakning, frysning och nötning orsakade mer omfattande skador på betongens yta än vad de enskilda mekanismerna gjorde tillsammans.

Den successiva nedbrytningen av betongytan längs vattenlinjen börjar med att ytskiktet urlakas under vår, sommar och höst. Betongens yta blir därmed känslig för frostangrepp och ytskiktet skadas under den följande vintern. På våren faller det skadade skiktet bort. Därefter börjar processen om på nytt.

I en del fall har inre skador påträffats vid och strax ovanför vattenlinjen i betong tillhörande vattenkraftverk uppförda företrädesvis innan 1950-talet. Resultat från försök i laboratoriet bekräftar att inre skador kan inträffa ovanför vattenlinjen i icke frostbeständig betong. Bestämning av fuktnivåer i befintliga konstruktioner och i provkroppar efter laboratorieförsök visar däremot att risken för inre skador vid och ovanför vattenlinjen är låg i frostbeständig betong.

En annan typ av inre skador har påträffats långt under vattenlinjen i tunna och dämmande betongkonstruktioner. Skadornas art kan karaktäriseras av spjälkning av större betongsjok. Den gemensamma faktorn för konstruktionerna är att de har utsatts för långa perioder av ensidig frysning under vintern. Genomförda studier har visat att låg betongkvalitet, samt effekter av åldring och defekter från byggtiden kan möjliggöra makroskopisk islinsbildning, vilken orsakar spjälkning.

I fullt frisk betong med vattencementtal (vct) lägre än 0.9 är dock risken för makroskopisk islinsbildning låg. I betong med inre sprickbildning till följd av frostskador kan däremot spjälkning inträffa inom några dagar oberoende av betongens vct. Även i betong med inre defekter, till exempel mindre håligheter, kan spjälkning inträffa. Högre kvalitet på betongen kräver dock längre perioder av ensidig frysning för att makroskopisk islinsbildning ska orsaka skador. Eftersom ofördelaktiga temperatur- och fuktförhållanden kan existera vintertid i tunna och dämmande betongkonstruktioner bör risken för spjälkning av betong beaktas.

Genom bestämning av vattenmättnadsgrader i en 55-årig damm har det visats att höga fuktnivåer i betong kan uppkomma över tid så att även frostbeständig betong riskerar skadas vid frostangrepp. Mikrostrukturella observationer av betongprover från dammen visade även att frostbeständigheten kan försämras över tid till följd av att luftporerna i betongen fylls med ettringit och kalciumhydroxid. Trots att höga fuktnivåer uppkommer över tid kan risken för en del frostskador minimeras genom att speciellt utsatta konstruktioner skyddas från frostangrepp.

Nyckelord: Vattenbyggnader, Dammar, Betong, Cement, Vattenabsorption, Vattenmättnadsgrad, Nedbrytning, Frostbeständighet, Spjälkning, Makroskopisk islinsbildning, Urlakning, Synergi

Symbols and abbreviations

D_l	Moisture transport coefficient	kg/(m·s·Pa)
J_l	Liquid flow	kg/(m^2·s)
J_s	Saturated flow	kg/(m^2·s)
J_v	Vapour flow	kg/(m^2·s)
k_p	Permeability coefficient	kg/m
m_{cap}	Mass of the sample at capillary saturation	kg
m_{sat}	Mass of the sample at saturation	kg
m_{sub}	Mass of the saturated sample submerged in water	kg
m_{wet}	Mass of the sample in the moist state	kg
m_{105}	Mass of the sample in the dry state	kg
P_o	Atmospheric pressure	Pa
P_h	Hydrostatic pressure	Pa
P_l	Pore water pressure	Pa
r	Pore radius	m
S	Degree of saturation	-
S_{cap}	Degree of capillary saturation	-
S_{cr}	Degree of critical saturation	-
T	Temperature	K
t_{cap}	Time to capillary saturation	s
t_{cr}	Time to critical degree of saturation	s
t_s	Time to saturation	s
V_{po}	Porosity (open)	-
V_{pt}	Porosity (total)	-
v	Water vapour content	kg/m^3
v_s	Saturated water vapour content	kg/m^3
x	Distance	m

δ_p	Vapour diffusion coefficient	m^2/s
η	Dynamic viscosity	Pa·s
θ	Contact angle between water and solid	°
σ	Surface tension	Pa
φ	Relative humidity	-
AAR	Alkali-aggregate reaction	-
ACR	Alkali-carbonate reaction	-
ASR	Alkali-silica reaction	-
BSE	Back-scattered electrons	-
C_3A	Calcium aluminium hydrates	-
C_4AF	Calcium aluminium iron hydrates	-
CH	Calcium hydroxide – $Ca(OH)_2$	-
C-S-H	Calcium silicate hydrates	-
EDS	Energy dispersive X-ray spectrometer	-
EPMA	Electron microprobe analyser	-
ITZ	Interfacial transition zone	-
RH	Relative humidity (φ)	-
SCMs	Supplementary cementitious materials	-
SEM	Scanning electron microscope	-
TGA	Thermogravimetric analyser	-
w/c	Water to cement (ratio)	-
XRD	X-ray diffractometer	-

Appended papers

This thesis is based on the following papers:

Paper I	Rosenqvist M, Oxfall M, Fridh K, Hassanzadeh M (2015) A test method to assess the frost resistance of concrete at the waterline of hydraulic structures, Materials and Structures, Vol.48, p.2403-2415
Paper II	Rosenqvist M, Fridh K, Hassanzadeh M, Long-term frost resistance of concrete in hydraulic structures: Comparison between laboratory and field studies, (submitted)
Paper III	Rosenqvist M, Pham L-W, Terzic A, Fridh K, Hassanzadeh M, Effects of interactions between leaching, frost action and abrasion on the surface deterioration of concrete, (submitted)
Paper IV	Rosenqvist M, Bertron A, Fridh K, Hassanzadeh M, Concrete alteration due to 55 years of exposure to river water: Chemical and mineralogical characterisation, (submitted)
Paper V	Rosenqvist M, Bertron A, Fridh K, Hassanzadeh M, Effects of surface leaching on the frost resistance of concrete with long-term exposure to river water, (manuscript)
Paper VI	Rosenqvist M, Fridh K, Hassanzadeh M (2012) Macroscopic ice lens growth: Observations on Swedish concrete dams, Proceedings of the 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, p.658-664
Paper VII	Rosenqvist M, Fridh K, Hassanzadeh M (2016) Macroscopic ice lens growth in hardened concrete, Cement and Concrete Research, Vol.88, p.114-125

The contributions of the authors to the papers included in this thesis are as follows:

Paper I	MR designed the study together with the co-authors. MH had the initial idea for the study. MR and MO conducted the experimental work. Methodical details were discussed by the authors during the study. MR wrote the paper. KF and MH commented on the manuscript.
Paper II	MR designed the studies together with the co-authors. MR conducted the experimental work, evaluated the data and wrote the paper. Methodical details were discussed with KF and MH who also commented on the manuscript.
Paper III	MR designed the study. LWP and AT performed the experimental work. MR evaluated the data and wrote the paper. Methodical details were discussed with KF and MH who also commented on the manuscript.
Paper IV	MR designed the study together with AB. MR conducted the experimental work, evaluated the data and wrote the paper. Methodical details were discussed with AB. AB, KF and MH contributed with comments on the manuscript.
Paper V	MR designed the study together with the co-authors. MR conducted the experimental work, evaluated the data and wrote the paper except some parts concerning low-temperature calorimetry which were written by KF. Methodical details were discussed with AB, KF and MH who also commented on the manuscript.
Paper VI	MR designed the study together with the co-authors. MR conducted the experimental work, evaluated the data and wrote the paper. Methodical details were discussed with KF and MH who also commented on the manuscript.
Paper VII	MR designed the study together with the co-authors. MR conducted the experimental work, evaluated the data and wrote the paper except some parts concerning fracture mechanics which were written by MH. Methodical details were discussed with KF and MH who also commented on the manuscript.

Contents

1 Introduction

1.1 Background

A structure built in any body of water with the purpose to control or change the natural flow of water is termed a hydraulic structure. Hydro power stations, dams, locks, canals and harbours are all examples of hydraulic structures. Bridge piles in water only affect the water flow to some extent, but are also referred to as hydraulic structures in this thesis.

There are approximately 2 000 hydro power plants and more than 30 000 bridges in Sweden. Concrete structures submerged or partially submerged in water can be found at most hydraulic structures. In the case of bridges, not all of them are built of concrete and not all of them have piles in water. Despite this, the total value of all hydraulic structures built of concrete in Sweden is tens of billions of Euros.

It is well known that concrete structures submerged or partially submerged in water and occasionally subjected to frost action are at risk of frost damage due to high water saturation levels in the concrete. Frost action is defined as the combined effects of freezing and thawing with varying durations. Since concrete with high saturation levels is susceptible to frost damage, the frost resistance is a very important characteristic of concrete in hydraulic structures.

The design life of hydraulic structures of concrete traditionally ranges from 50 to 100 years. The expected useful lifetime of these structures, termed the service life, has normally been the same as the design life. Over time however, it has become economically attractive to extend the service life of many structures still in use. One of the consequences of extending the service life without taking measures is that it exceeds the original design life. Hence, service life extension of hydraulic structures is closely related to the durability of concrete.

Durability of concrete is defined as the ability to resist actions of weathering or any other deterioration processes. The durability of concrete is a concern to owners of concrete structures since it is strongly related to their performance and safety. For example, the use of low quality concrete increases the risk of additional costs due to the need for repairs or replacement of damaged structures.

Deterioration of concrete can be caused by many different events. Durability problems, such as the risk of frost damage of concrete, are often associated with high saturation levels. Concrete submerged or partially submerged in water may also be deteriorated by exposure to soft water or aggressive agents, such as chlorides and sulphates. Moreover, extensive cracking of concrete can be caused by extreme loads, seasonal temperature variations and chemical reactions between cement and aggregate causing swelling.

In order to understand the long-term performance and durability of concrete structures in various environments, detailed knowledge about ageing and degradation mechanisms is crucial. Such knowledge can be used to design concrete mixes with adequate ability to resist deterioration. Moreover, detailed knowledge about deterioration processes is important in order to improve the efficiency of maintenance of existing structures. However, access to detailed knowledge about the deterioration processes of concrete is a prerequisite to secure and to be able to safely extend the service life of concrete structures.

1.2 Presentation of the thesis

Owing to the climatic conditions in Sweden, the effects of frost action may have a considerable impact on the deterioration of concrete in hydraulic structures. Field observations of superficial and internal damage to concrete, which are suspected to be frost-induced, have been made at many Swedish hydro power plants. These observations have raised questions about the long-term performance of concrete structures in contact with fresh water in cold regions.

Based on the observations of concrete damage and the fact that the service life may exceed the design life of many hydraulic structures, the following questions were identified with respect to the long-term performance and durability of concrete:

- Which degradation mechanisms are causing progressive deterioration of the concrete surface at the waterline of hydro power structures?

- Is there any risk of internal frost damage to concrete at and above the maximum water level of hydro power structures?

- What are the conditions for spalling of concrete in thin water retaining concrete structures subjected to long periods of freezing temperatures?

- How is the frost resistance of air-entrained concrete affected by long-term submersion in water?

The information obtained by answering these four questions can be used to more accurately determine where frost damage is likely to occur and how the effects of frost action should be minimised. The choice of repair materials can also be based on knowledge about the deterioration processes. Finally, the information can be used as input in models to predict the service life of hydraulic structures.

Observations of surface deterioration of concrete at the waterline of hydro power structures formed the basis for the experimental studies to address the first question. The frost resistance of concrete was determined by standardised tests as well as non-standardised tests simulating climatic conditions similar to those prevailing at the waterline of hydraulic structures in cold regions. Moreover, the effects of interactions between leaching, frost action and abrasion on the surface deterioration of concrete were also considered since hydraulic structures are often subjected to multiple degradation mechanisms. To compare the results of the laboratory experiments, concrete from an existing 55-year-old dam was used to characterise the chemical, mineralogical and physical changes in the cement paste related to long-term exposure to river water.

The second question was also addressed by subjecting concrete specimens to climatic conditions similar to those prevailing at the waterline of hydraulic structures in cold regions. Water saturation levels obtained in the specimens were determined to assess whether the critical degree of saturation can be exceeded during freeze-thaw conditions. To evaluate the accuracy of the non-standardised test, the results on the saturation levels were compared to saturation levels in the 55-year-old concrete dam at, above and below the normal water level.

Field observations of concrete spalling on the upstream and downstream face of some thin concrete dams formed the basis for the experimental studies to address the third question. Concrete specimens were subjected to unidirectional freezing in a laboratory test. Three different types of specimens were used to assess the conditions for macroscopic ice lens growth in hardened concrete. Macroscopic ice lens growth is generally known as frost heave when it occurs in soils in winter.

The fourth question addressed the concerns about the long-term performance of air-entrained concrete submerged or partially submerged in water. If water or secondary precipitates gradually replace the entrained air, the frost resistance will be reduced. To assess the effects of long-term submersion of air-entrained concrete in water, the saturation levels in specimens submerged at different depths were determined after 28 months. Furthermore, the saturation levels obtained in the specimens were compared to saturation levels in concrete originating from the upstream face of the 55-year-old dam.

1.3 Scope and limitations

Observations of concrete deterioration in hydro power structures in Sweden form the basis for the case studies performed in this thesis. The experimental work is focused on the effects of frost-induced deterioration of concrete in contact with fresh water. Hence, the effects of de-icing chemicals on the freeze-thaw resistance of concrete are not considered. The results of the experimental studies presented in this thesis are in many cases applicable to other hydraulic structures exposed to similar environmental exposure conditions. Moreover, the results may also be useful to understand the deterioration processes of hydraulic structures built of concrete in other countries in cold regions.

Concrete of poor quality was generally used for the construction of hydro power structures and other hydraulic structures in the early 20th century in Sweden. Many of those structures were severely damaged, and extensive repairs were carried out only a few decades later. Since the repaired concrete in those structures differs from the original concrete, there is no need to study the long-term performance and durability of those original types of concrete. The experimental work in this thesis is therefore focused only on concrete used for the construction of hydro power structures between the 1930s and 1970s.

CEM I cements were used (with a few exceptions) for the construction of major hydro power plants in Sweden. Since this thesis focuses on the deterioration processes of concrete in existing structures, CEM I cement is used in most of the studies.

2 Hydro power in Sweden

2.1 Hydro power development

The development of hydro power for electricity production was initiated in the late 19th century and made the large scale industrialisation in Sweden possible. The increasing demand for electricity led to a boom in the number of power plants commissioned during the early 20th century. Unfortunately, several large hydro power projects were cancelled or postponed due to weaker demand for electricity during the economic crisis in the 1920s. However, from the mid-1930s until the first nuclear power plants were put into commercial operation in the 1970s, there was a constant risk of electricity shortage in Sweden. The majority of the large hydro power plants were commissioned between 1945 and 1975.

According to Swedish Energy (2015), about 2 000 hydro power plants are currently in operation in Sweden, for a total installed capacity of roughly 16 200 MW. About 200 of the power plants have an installed capacity of 10 MW or more. In a year of normal water runoff, about 65 TWh of electricity is produced, corresponding to approximately 40 % of the electricity used in Sweden each year.

In times of concern about the impact of global climate change due to emissions of greenhouse gases, the emissions of carbon dioxide (CO_2) from the hydro power industry is relatively low. Hydro power has so far contributed to the welfare of people and society in many ways. The utilisation of renewable energy sources, such as hydro power, is therefore one of the keys to a sustainable future.

Hydro power plants are used to generate electricity from the gravitational force of falling water. At the intake, water enters the power plant and gravity causes it to fall through the penstock (Figure 2-1). At the end of the penstock, the movement of the water causes the turbine to rotate and the potential energy of the water is converted into mechanical energy. A generator is attached to the same shaft as the turbine and the rotating generator converts the mechanical energy into electricity. The used water then re-enters the river through the draft tube.

The power available for electricity production is basically determined by the river flow rate and difference in water levels between the upstream and downstream sides of the dam. This difference in water levels is known as the head. The most common purposes of dams is to control rivers, store water for irrigation or increase the head to generate electricity in power plants. Above ground power plants and spillways built of concrete can normally be found adjacent to the dam (Figure 2-2). Most dams in Sweden are either embankment or concrete dams.

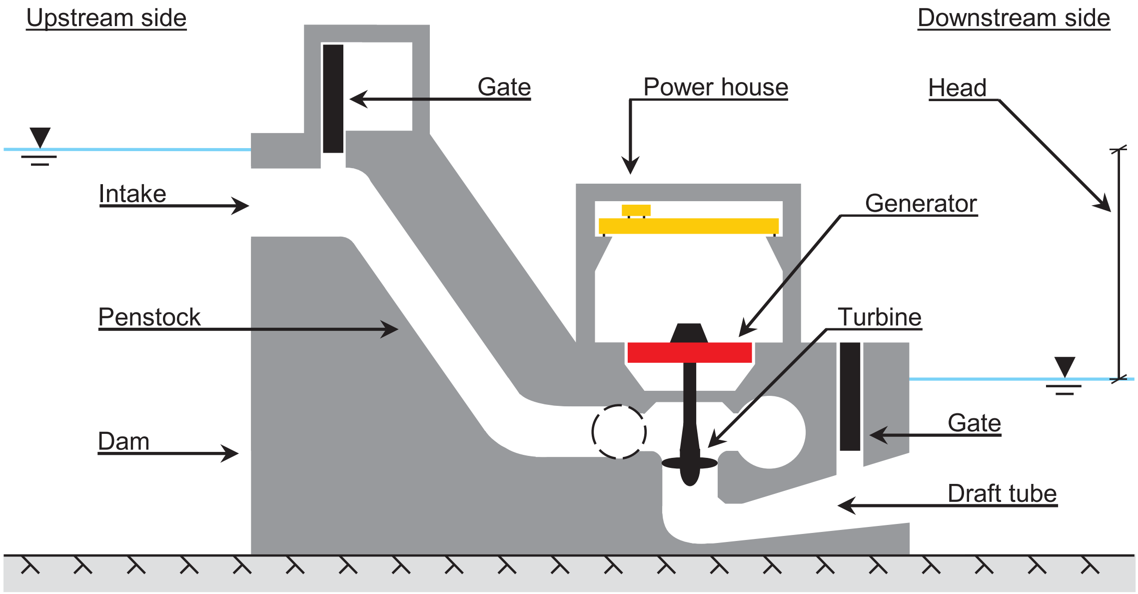

Figure 2-1. Cross section of a hydro power plant.

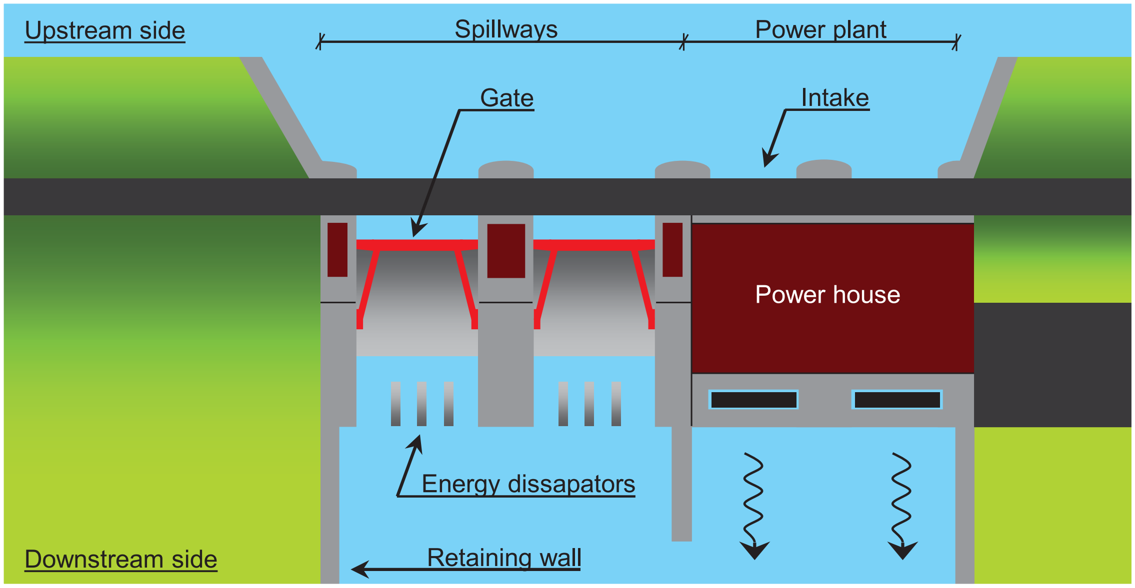

Figure 2-2. Hydro power plant diagram. Electricity is generated in the power house, whereas surplus water can be released in the spillway.

2.2 Concrete technology

In the early 20th century, reinforced concrete was a new building material in Sweden. Löfquist (1955) reported that tamped concrete of dry consistency was used for the construction of hydro power structures during the first decades of the 20th century. CEM I cements were used as a binder. In unreinforced structures, such as solid gravity dams, the cement content was normally less than 200 kg/m^3 resulting in non-water tight concrete. To ensure water tightness of the dam, cement-rich concrete was used in the outermost water-facing layer.

Proper tamping of dry concrete mixes in narrow forms filled with reinforcing steel bars was difficult to achieve in this early stage. Instead, the practice of chuting concrete into place was introduced. To allow the concrete to flow in chutes, the use of very wet mixes was required. Concrete mixes with a water to cement ratio (w/c-ratio) up to 1.0 were used. The use of lean mixes with a high w/c-ratio led to an almost immediate leaching of the concrete due to percolating water.

In order to make concrete less permeable, the cement content was increased to approximately 275-350 kg/m^3 in the late 1920s (Löfquist, 1955). The amount of fine particles in the concrete mixes was also increased. Moreover, the w/c-ratio was reduced to about 0.6. However, increasing the cement content of concrete increases the risk of thermal cracking due to heat evolution during the cement hydration and subsequent contraction of the hardened concrete during cooling. New cements had to be developed as a countermove.

The low-heat Portland cement (known as Limhamn LH) developed by Forsén (1936) following a request from the Vattenfall company in the early 1930s bears mentioning; Vattenfall was formerly known as Kungliga Vattenfallsstyrelsen (The Royal Board of Waterfalls) and later as Statens Vattenfallsverk (Swedish State Power Board). The Limhamn LH cement was developed to reduce the heat evolution of concrete during hydration and to improve its resistance to calcium leaching by enrichment in silica. These objectives were achieved by grinding the cement more coarsely and increasing the C_2S content while decreasing the C_3S content. The Limhamn LH cement, together with the ordinary Portland cement (Limhamn Std), became the most used cements during the major part of the Swedish hydro power development.

The workability of the fresh concrete was reduced when the low-heat cement was used. In less successful attempts to improve the workability, Lalin (1948) added different powdered admixtures to the mix, such as diatomaceous earth. Adding lathering albuminoids (globular proteins from egg white) to the mix improved the workability. Albuminoids were used for the first time in concrete by Vattenfall during the heightening of multiple-arch dams at Suorva in 1937. As a side benefit, normal dosage of albuminoids increased the air content of the concrete to approximately 3–5 %. Hence, the frost resistance of concrete was improved. With the introduction of vibrators, plasticisers and improved air entraining agents, such as Vinsol Resin and Darex AEA, the w/c-ratio was reduced to 0.50–0.55 during the 1950s. In spite of continuous development, no further significant advances in the concrete mix design for hydro power structures were made until the end of the major hydro power development era in the late 1970s.

In addition to the Limhamn LH cement, other cements were developed as well. Pansarcement was introduced in the 1930s, being a cement blend consisting of Limhamn Std or Limhamn LH interground with metakaolin. In the former case, the metakaolin content was 20–25 %, whereas it was 10–15 % in the latter case (Forsén, 1936). Further attempts to reduce the heat generation were made during the 1950s when trass was interground with CEM I cements. Trass is the local name (in Eifel) of a volcanic tuff that is rock from volcanic ash. The trass content of the cement was approximately 30 %. Another attempt was the introduction of Vulkancement during the 1950s; it was a blend of CEM I cements and leftover slag from iron production. The slag content varied between 25 and 50 % throughout the year to counter the effects of summer and winter temperatures. These cement blends saw only limited use in the construction of hydro power plants.

Shortage of coal supplies during the Second World War resulted in rationing of cement and the subsequent development of replacement cement (E-cement). The E-cement was composed of approximately 50–70 % Portland cement and 30–50 % granulated blast furnace slag, silica or lime (Sandberg, 1942). However, CEM I cements were still used for the construction of large hydro power plants due to their importance to meet the growth in demand for electricity. The E-cement may have been used for many of the small hydro power plants constructed throughout the 1940s. Eriksson (2002) reported that the performance and durability of hydro power structures built of concrete with E-cement varies greatly.

From a general point of view, proper execution of the concrete work in accordance with instructions has gradually improved the durability of concrete in hydro power structures. The introduction of the Limhamn LH cement and air entraining agents have been key elements for the durability of concrete in Swedish hydro power plants built between the early 1930s and the late 1970s. However, the long-term performance and durability of concrete in hydro power structures depend on factors such as variations in the cement producer, workmanship of different skills or local variations in the environmental exposure conditions.

2.3 Environmental exposure conditions

2.3.1 Temperature conditions

The climate in Sweden is variable, with warm summers and cold winters. In the southern parts of the country, the monthly average temperature varies between -1 in winter and +16 °C in summer (Nevander and Elmarsson, 2006). In the northern parts of Sweden, the corresponding values are -14 and +12 °C. The difference between daily minimum temperatures in winter and daily maximum temperatures in summer is usually in the range of 50 to 60 °C. Air temperatures down to -30 °C, which can persist for weeks, are common during the winter in the northern regions of the country.

The temperature of concrete in hydraulic structures, and especially in the surface, generally follows the changes in the air temperature. In addition, the direction of the surface with regard to the four cardinal points and the inclination of the surface also affect the temperature of the concrete surface to some extent. The temperature of a concrete surface may increase due to solar radiation. On the contrary, the loss of heat by radiation at night may lead to the fact that the surface temperature becomes lower than the air temperature.

In spring and autumn, the air temperature frequently crosses the freezing point of water. Krus (1996) theoretically showed that concrete structures can be subjected to up to 50 freeze-thaw cycles over a year in northern Sweden. However, the number of freeze-thaw cycles decreases with increasing amplitude between the freezing and thawing temperatures. This means that the number of freeze-thaw cycles in the northern parts of Sweden generally is less than in the south.

2.3.2 Ice conditions

Due to freezing temperatures in the air, the surface of water bodies is normally covered with ice in winter. Formation of ice covers can be delayed by strong winds mixing surface water with the warmer lower water layer. Hence, large bodies of water will often have a delayed ice formation compared with smaller water bodies having similar climate conditions. In lakes and slow flowing parts of a river, the formation of ice covers usually starts along the shores, banks or on calm bays. According to ICOLD (1996), ice covers may start to form when the bulk temperature of the river is 1 or 2 degrees above the freezing point.

Formation of ice covers can also be prevented by turbulent water flow. Open water surfaces can thus be seen at intakes, spillways and on the downstream side of power houses. In spite of open water surfaces and a water temperature above the freezing point, a band of ice frozen solid to the concrete surface can be seen at and below the waterline of hydraulic structures (Figure 2-3 a). Formation of ice on the concrete surface indicates freezing temperatures in the concrete.

The band of ice falls off when the air temperature starts to rise in spring (Figure 2-3 b). However, as previously mentioned, the air temperature frequently crosses the freezing point of water in spring and autumn. Depending on the air temperatures, the band of ice can be re-formed during the nights and later melted away during the days (Figure 2-3 c–d).

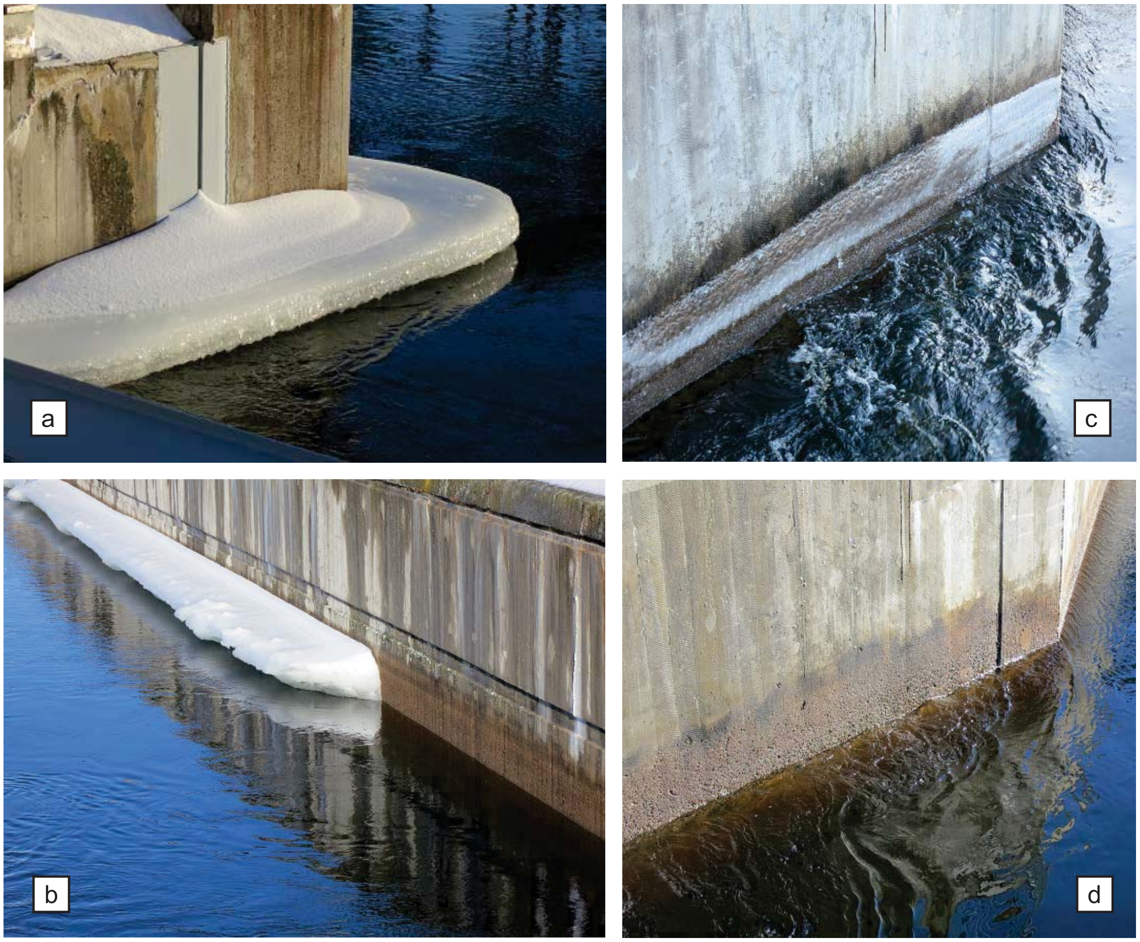

Figure 2-3. In winter, a band of ice frozen solid to the concrete surface can be seen at the waterline of hydraulic structures (a). In spring, the band of ice falls off when the air temperature rises (b). In both spring and autumn, the air temperature frequently crosses the freezing point of water. A small band of ice can therefore be seen at the waterline in the morning (c) while it has been melted away in the evening (d).

Due to fluctuations in temperature, ice expands and contracts like any other solid. Hence, any structure preventing the expansion accompanied by warming of an ice cover will be subject to thrust due to thermal expansion of the ice. Fluctuating water levels (Figure 2-5 a–b) can exert forces on structures to which the ice cover is frozen. However, ICOLD (1996) reported that water level fluctuations may provoke formation of active cracks in the ice cover approximately parallel to shores, banks and the upstream face of dams (Figure 2-4 c). The cracks divide the ice cover into three separate parts. One part of the ice cover remains frozen solid to the dam face, whereas the other two parts float freely in response to the change in water level (Figure 2-4 d). Hence, the band of ice frozen solid to the dam face may protect the concrete surface from abrasive wear by the ice cover.

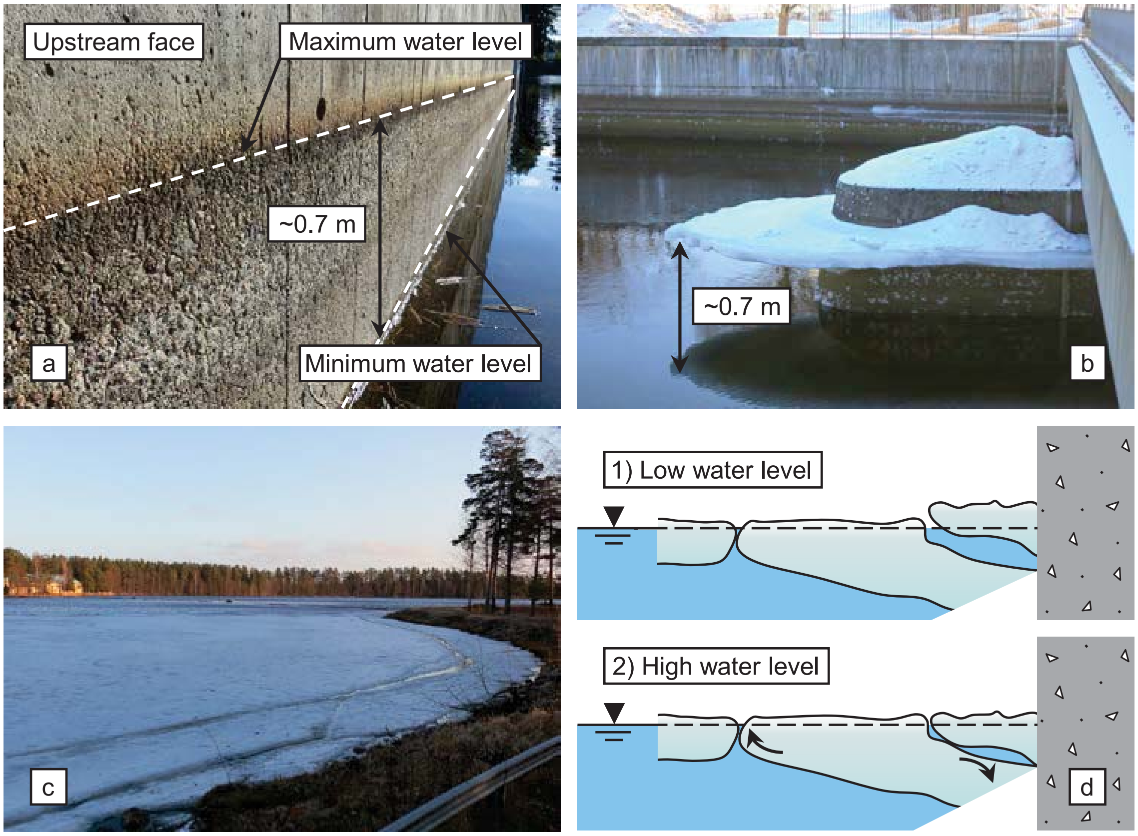

Figure 2-4. Fluctuations in hydro power reservoir water levels occur (a–b) throughout the year. Such fluctuations may provoke formation of cracks parallel to shores, banks and the upstream face of dams (c). One part of the ice cover remains frozen solid to the dam face (d). Image (d) based is on a figure in ICOLD (1996).

ICOLD (1996) stated that the ice cover tends to melt in place in small and medium sized lakes and reservoirs. In rivers fully utilised for power production, the ice tends to melt in place or will at least be strongly weakened before it breaks up into ice floes of different sizes during spring. The ice floes are then slowly brought downstream by the river current. If the ice floes do not melt away until they reach the dam or any other hydraulic structure, the ice floes push against the structure until they break apart into smaller pieces or melt away (Figure 2-5).

Figure 2-5. Ice floe pushing against the dam and a bridge pile.

2.3.3 River water conditions

The impact of river water on the chemistry of concrete is complex due to the varying types and concentrations of ions present in the water. According to Allan and Castillo (2007), dissolved minerals from weathered bedrock, woods and fields, along with (acidic) rain and naturally dissolved CO_2 in water, affect the chemical composition and pH of river water. Hence, the water chemistry of the water body concerned may have a great effect on the durability of concrete.

Chemical analysis of Swedish river water has been conducted at or close to river mouths monthly since the 1960s. Table 2-1 presents average pH levels and concentrations of Ca, Si, Al, Fe, Mg, Na, K and SO4 ions for 15 different Swedish rivers. The data is available from SLU (2016). For comparison, the table presents the composition of seawater and the limiting values for a slightly aggressive chemical environment (XA1) stated in EN 206; see SIS (2013).

By comparing the limiting values with the results of the chemical analyses of the river waters, it can be concluded that the river waters do not fulfil the conditions for XA1. However, many of the river waters can be regarded as soft water due to their low concentrations of ions, particularly calcium (Ca) and magnesium (Mg) ions. This is especially true for river waters in the central and northern parts of Sweden where the bedrock mainly consists of gneisses and granites.

In some parts of the southern country, the bedrock is characterised by limestone, shale and sandstone. The concentrations of, for example, Ca in the southern river waters are consequently higher than in the northern river waters. Because of the geology of Sweden, the ion concentrations of the water in Swedish rivers are low in comparison with seawater and most other rivers around the world.

Ion concentration and pH levels vary throughout the year due to seasonal changes in the flow of water in rivers. According to the measurements by Drugge (2001), the ion concentration of the water in the river Lule älv seems to be temporarily lowered during the snowmelt runoff period. For example, measurements conducted in June and July showed a significantly lower concentration of Ca in the river water compared to measurements conducted in August and September.

Normal pH values in Swedish lakes and rivers vary in the range 6 to 8 depending on the geological conditions around the water bodies (Bydén et al., 2003). pH values below that range may indicate acidification of the surface water. To further use the river Lule älv as an example, the pH value was somewhat lower in June and July than it was in August and September (Drugge, 2001). The lower concentrations of alkali ions in the river water during the snowmelt runoff period may explain the lower pH values in June and July.

As mentioned in Section 1.1, soft water can have a detrimental effect on the durability of concrete. Leaching combined with frost action and abrasion may have an even greater effect on the deterioration of concrete than only frost action has. In the long term, it is the ability of the concrete to resist the environmental exposure conditions that ultimately determines the service life of hydraulic structures. The deterioration processes of concrete must therefore be known.

Table 2-1. Average pH and chemical composition of water from 15 Swedish rivers (SLU, 2016).

River	pH	Ca	Si	Al	Fe	SO_4	Mg	Na	K
	[-]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]
Kävlinge å	7.81	77.89	3.21	0.07	0.28	42.53	6.02	17.83	5.40
Rönne å	7.48	32.84	3.22	0.12	0.64	31.20	3.77	13.12	2.55
Lagan	6.61	5.98	2.01	0.12	0.83	11.70	1.68	6.50	1.25
Nissan	6.57	6.55	2.96	0.21	1.11	15.22	1.97	8.55	1.27
Göta älv	7.13	7.47	0.42	0.12	0.13	14.68	1.50	6.28	1.20
Motala ström	7.48	20.93	0.81	0.11	0.16	25.80	2.72	9.78	2.05
Klarälven	6.60	2.83	1.90	0.11	0.44	3.71	0.66	1.49	0.49
Dalälven	6.92	5.22	1.93	0.10	0.30	6.15	0.82	2.05	0.60
Ljusnan	6.86	4.11	2.57	0.07	0.29	3.98	0.85	1.81	0.56
Ljungan	7.19	7.74	1.98	0.04	0.15	3.98	0.94	1.50	0.57
Indalsälven	7.25	7.67	0.93	0.03	0.07	3.65	0.69	1.44	0.42
Ångermanälven	6.93	3.92	1.37	0.05	0.20	3.08	0.80	1.19	0.41
Ume älv	6.99	4.12	1.46	0.08	0.23	3.22	0.71	1.17	0.52
Skellefte älv	6.84	3.86	1.24	0.03	0.22	4.03	0.53	1.20	0.51
Lule älv	6.87	3.05	1.19	0.04	0.21	2.94	0.68	1.50	0.51
XA1 (SIS, 2013)	6.5-5.5	-	-	-	-	200-600	300-1000	-	-
Seawater (DOE, 1994)	8.1	412	-	-	-	2 712	1 284	10 784	399

2.4 Deterioration of concrete under different conditions

In the following sections, three examples of different exposure conditions of hydraulic structures will be presented together with the associated damage. All structures are in contact with fresh water and also exposed to great temperature fluctuations over the years.

2.4.1 Deterioration of concrete at the waterline

Progressive deterioration of the concrete surface can be seen at the waterline of hydro power structures built of both non-air-entrained and air-entrained concrete. The deterioration results in the exposure of coarse aggregate and eventually the reinforcing steel. Field observations indicate deterioration rates of up to 1 mm per year. The surface deterioration is generally distributed evenly along the waterline. However, the greatest amount of damage is concentrated to the waterline and decreases with increasing depth from the normal water level.

Air temperatures as low as -30 °C can occur in winter, and yet the bulk water temperature remains above freezing. Large temperature gradients may therefore occur in the concrete at the waterline. If the water body in question is not covered with ice during the winter, a band of ice is frozen solid to the concrete surface at the waterline (Figure 2-3). An example of annual temperature conditions at the waterline is shown in Figure 2-6 (a).

Figure 2-6 (b–d) shows three examples of surface deterioration at the waterline of hydro power structures. This type of concrete damage to hydraulic structures is commonly assumed to be caused by ice floes and driftwood. Abrasive wear of the concrete surface may occur if the objects push against the structures. This scenario applies to hydro power intakes and spillways on the upstream side where the river current leads ice floes and driftwood to the structures. The same scenario also applies to the upstream side of bridge piles in rivers. Figure 2-6 (b–c) shows two examples of superficial damage to the upstream face of two concrete dams.

On the downstream side of hydro power structures, the river current leads ice floes and driftwood away from the structures. In spite of this fact, surface deterioration to the same extent can be seen on the downstream side (Figure 2-6 d). Such observations indicate that progressive deterioration of the concrete surface at the waterline is not exclusively caused by abrasive action.

Moreover, hydro power structures may also suffer from internal damage just above the maximum water level (Figure 2-6 e). In this case, coarse aggregates were exposed and the concrete appeared soft and deteriorated. This type of damage has been observed mostly on hydro power structures constructed before the 1950s.

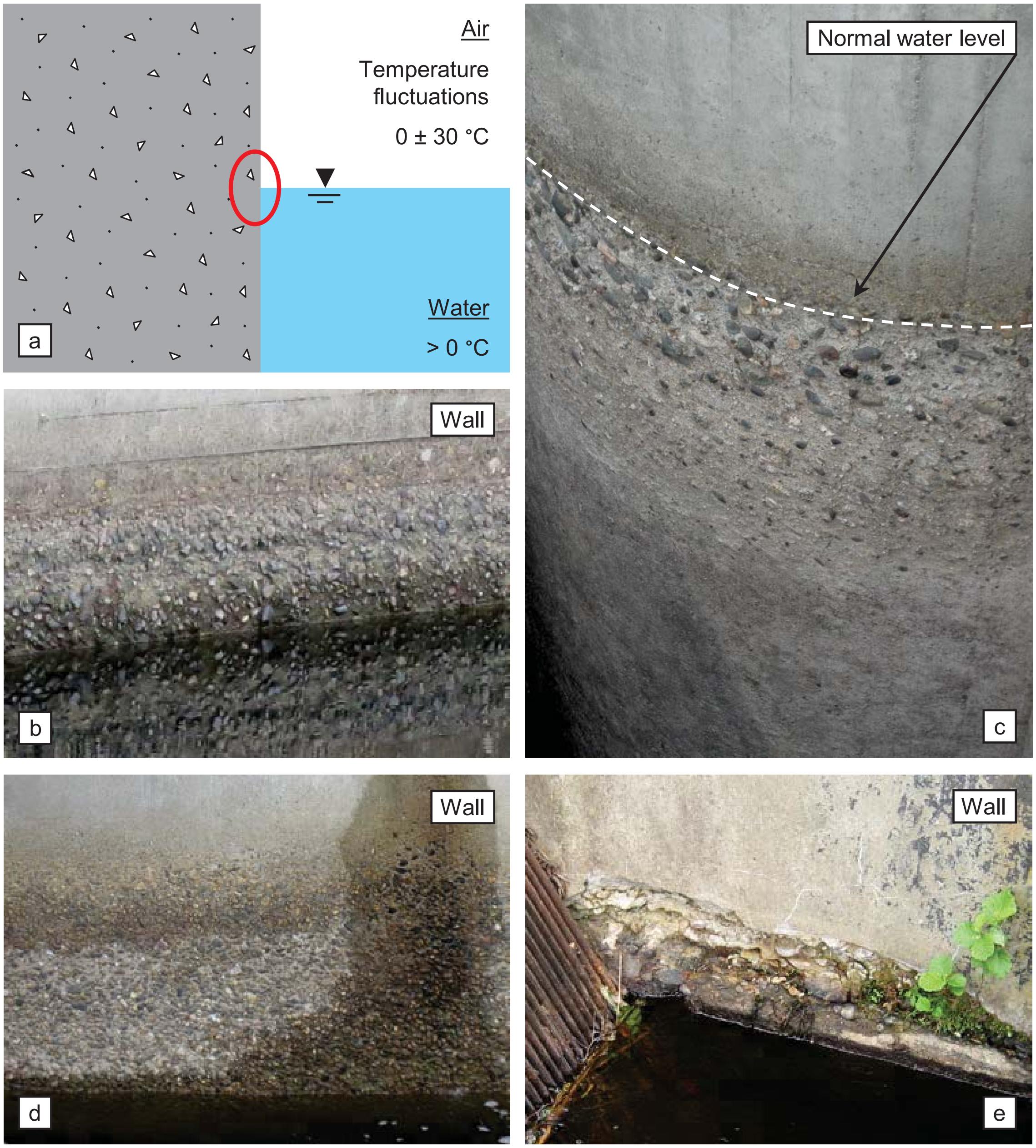

Figure 2-6. Temperature conditions at the waterline are shown in (a). Photos (b–d) show three examples of surface deterioration of concrete at the waterline of hydro power structures. Photos (b–c) are taken on the upstream side whereas photo (d) is taken on the downstream side. Photo (e) shows an example of internal damage above the waterline.

With the desire to better understand the long-term performance and durability of concrete in hydraulic structures in cold regions, there is an apparent need to determine the degradation mechanisms that cause progressive deterioration of the concrete surface at the waterline. Furthermore, there is also a need to determine whether there is any risk of internal frost damage to concrete at and above the maximum water level of hydraulic structures in cold regions.

2.4.2 Deterioration of concrete where the water level fluctuates

Delamination of the vertical concrete surface has been observed on the upstream face of hydro power structures subjected to large water level fluctuations. Many dammed river reservoirs in cold regions are filled up during the snowmelt and summer periods. To produce electricity during the subsequent winter, the water level is gradually lowered during the coldest period of the year. Annual water level fluctuations up to 35 m occur in some Swedish hydro power reservoirs. The upstream face of those structures is thus alternately exposed to air and water (Figure 2-7 a). Air temperatures as low as -30 °C may occur in winter and subject concrete (that until recently had been underwater) to sudden freezing.

Figure 2-7 (b–c) shows the upstream side of a spillway structure that has been alternately above and below water since the early 1960s. Internal damage due to delamination of the concrete that covers the reinforcing steel can be seen in Figure 2-7 (d–e). Prior to the rehabilitation of the spillway structure, water jetting was used to remove damaged concrete in order to estimate the depth of deterioration.

Concrete was easily removed to a depth of 200 mm where the water jetting was stopped. The actual depth of deterioration may have been even greater in some locations. It was noted that the delamination of the concrete occurred in the concrete cover as well as behind the reinforcement. Similar damage was observed in other locations on the spillway structure, including the horizontal crest in front of the spillway gates on the upstream side of the spillway structure. It was also noted that the reinforcing steel was in good condition.

The causes of the damage to the spillway structure were never determined. Due to the climatic conditions in the area, it is reasonable to suspect that the damage was caused by frost action. It is unknown to the author whether or not the concrete was air-entrained. Nevertheless, the use of air entraining agents for the construction of hydro power structures became common practice in the 1950s.

In spite of the fact that the use of air entraining agents generally improves the frost resistance of concrete, there are still concerns about the long-term frost resistance of air-entrained concrete submerged or partially submerged in water. If the entrained air voids gradually fill with water, there is a risk that the frost resistance of concrete can be reduced over time. This risk needs to be assessed.

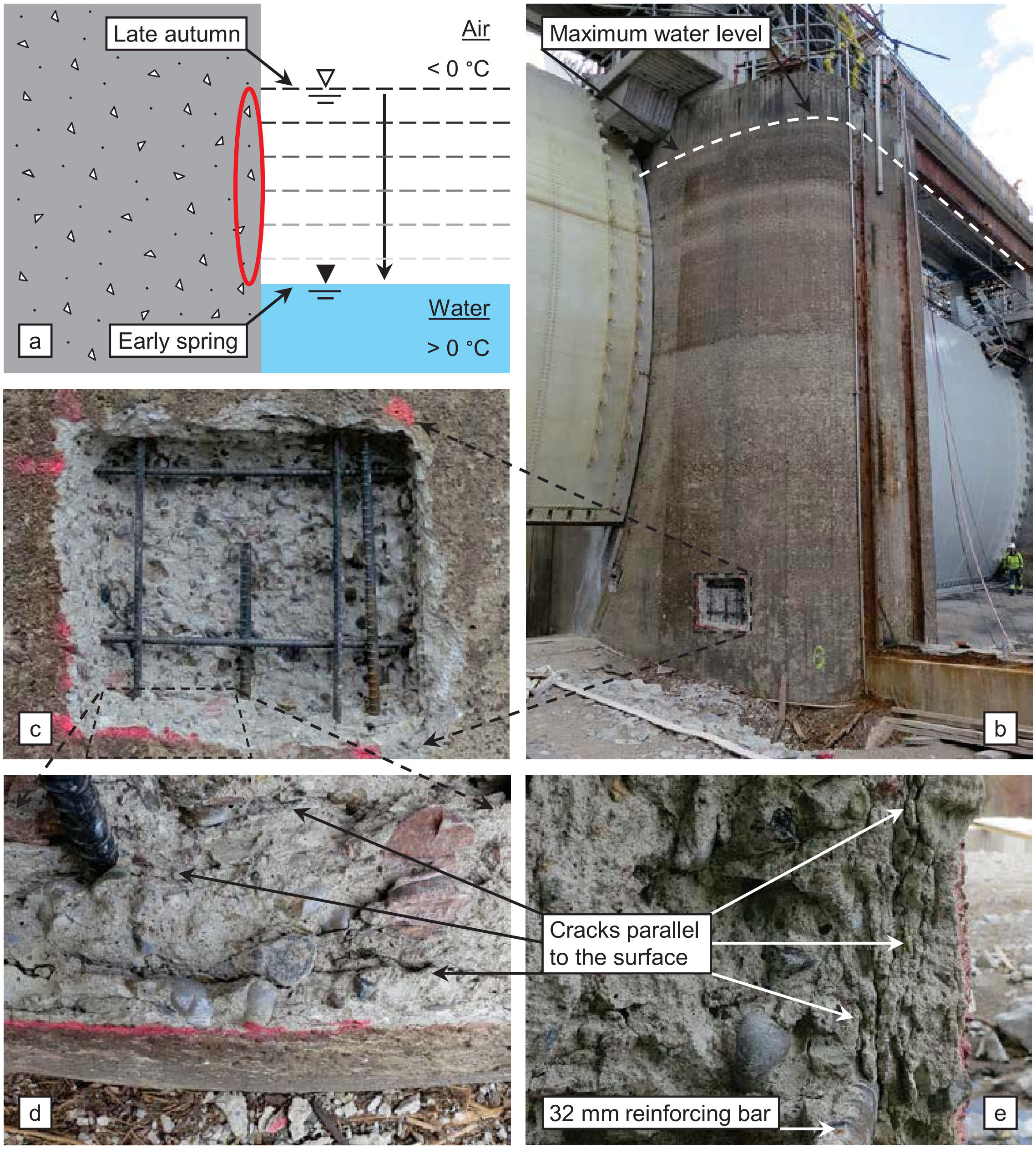

Figure 2-7. Temperature and water level conditions of hydro power structures subjected to great water level fluctuations are shown in (a). Photos (b–c) show the upstream side of a spillway structure where the water level is gradually lowered during the winter. Photos (d–e) show cracks parallel to the vertical surface due to delamination of concrete in the concrete cover as well as behind the reinforcement.

2.4.3 Spalling of concrete in thin concrete dams

Spalling of concrete has been observed far below the water level on the upstream face of some thin concrete dams. During inspections, divers have been able to remove pieces of concrete with their bare hands. Also on the downstream side of some thin dams, spalling of concrete has been observed. In the latter case, the damage was found in the vicinity of water leakage through cracks in the dams.

Thin concrete dams without heat insulating walls on the downstream side are exposed to large temperature gradients in winter. The temperature ranges from the ambient air temperature on the downstream side to the reservoir water temperature on the upstream side (Figure 2-8 a). Over the years, several cases have been reported with thin concrete dams suffering from severe spalling that has caused pieces of the concrete cover to come off (Figure 2-8 b–d). Deteriorated concrete has also been removed from behind the reinforcing steel.

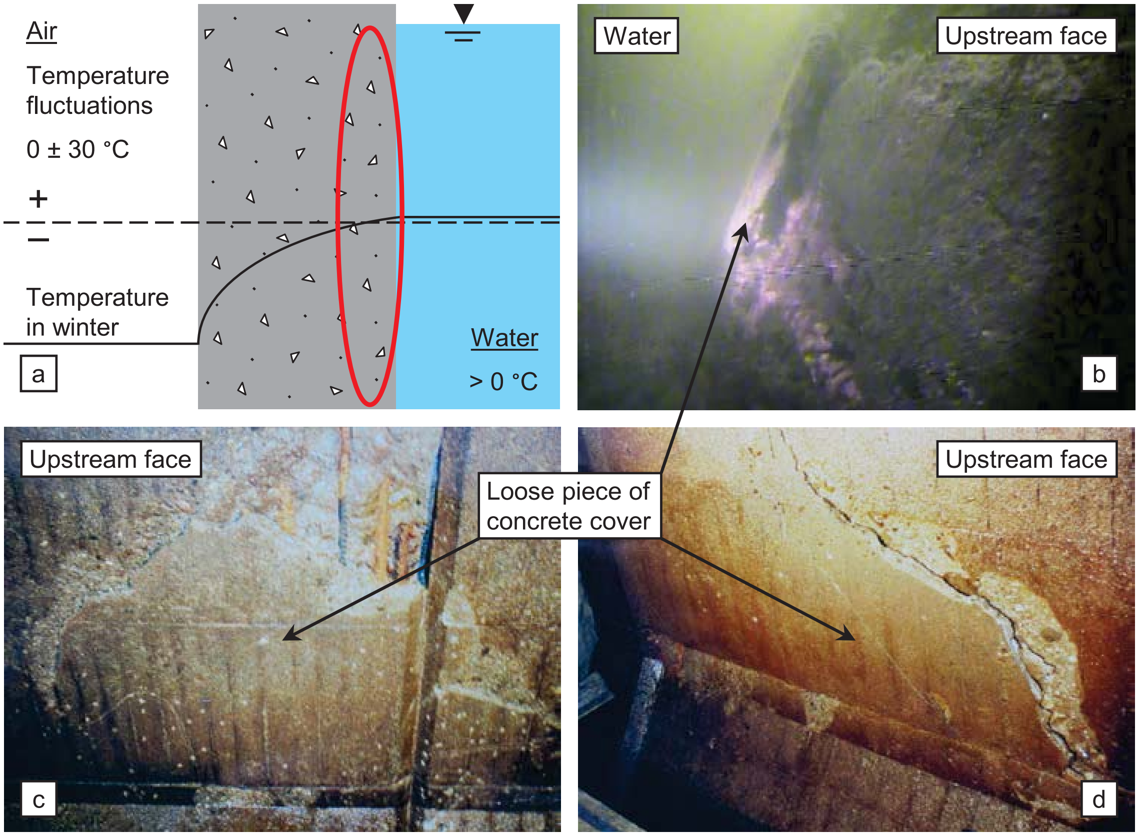

Figure 2-8. Approximate temperature distribution in thin concrete dams in winter (a). Photos (b–d) show pieces of the concrete cover that have come loose. Photos provided by Skellefteå Kraft AB and Uniper.

Example 1

Two of the largest concrete dams in Sweden were completed in 1954 (termed the 1954 dam) and 1958 (termed the 1958 dam). The 1954 dam is 40 m high and 1200 m long, including an 800 m long buttress dam (Figure 2-9 a), while the 1958 dam is 35 m high and 400 m long (Figure 2-9 b). The flat slab of both buttress dams is 1.2 m thick at the top and as much as 2.6 m thick at the base. None of the dams was provided with heat insulating walls on the downstream side when constructed.

In spite of similar structural design, the composition of the concrete differs between these two dams. During the construction of the 1954 dam, a standard Portland cement (Limhamn Std) was used as a binder. According to the guidelines for the design and construction of hydraulic structures, the cement content was allowed to vary between 310 and 350 kg/m^3 depending on the maximum aggregate size. The w/c-ratio here was approximately 0.5. An air entraining agent was added to the concrete mix to improve the frost resistance. Due to a lack of experience and uncertainties about the stability of entrained air, the concrete was hand tamped.

When the 1958 dam was under construction, the type of cement prescribed by the guidelines had changed. To reduce the risk of cracking due to the evolution of heat during the hardening process of concrete, a low-heat Portland cement (Limhamn LH) was used instead of the standard Portland cement. The cement content and the w/c-ratio were unchanged, whereas the concrete was vibrated instead of hand tamped during pouring.

Shortly after the completion of the 1954 dam, a considerable amount of cracks appeared in the flat slab. The cracking was mainly horizontal and worsened during the initial reservoir filling. Investigations conducted in the early 1960s showed that the cracks were continuous from one side of the flat slab to the other. Bergström and Nilsson (1962) reported that most of the cracks were developed in the lower part of the dam where the flat slab continuously becomes thicker.

Laboratory measurements showed that calcium was dissolved in the water leaking through the cracks. Frost damage was found in a few cases and only in the vicinity of leaking dilatation joints. About 30 years later, a second crack mapping showed that the number of cracks was tripled and the average length of the cracks was doubled (Fahlén and Näslund, 1991). Moreover, the concrete cover was missing in several places on the downstream face due to spalling of concrete. No evidence of corrosion of the reinforcing steel was found. Eriksson (1994) reported that spalling of concrete was also observed on the upstream face between the maximum water level and some 10 to 12 m down (Figure 2-9 c–d). The damaged areas varied between 0.5 and 10 m^2 in size and they were up to 200 mm in depth.

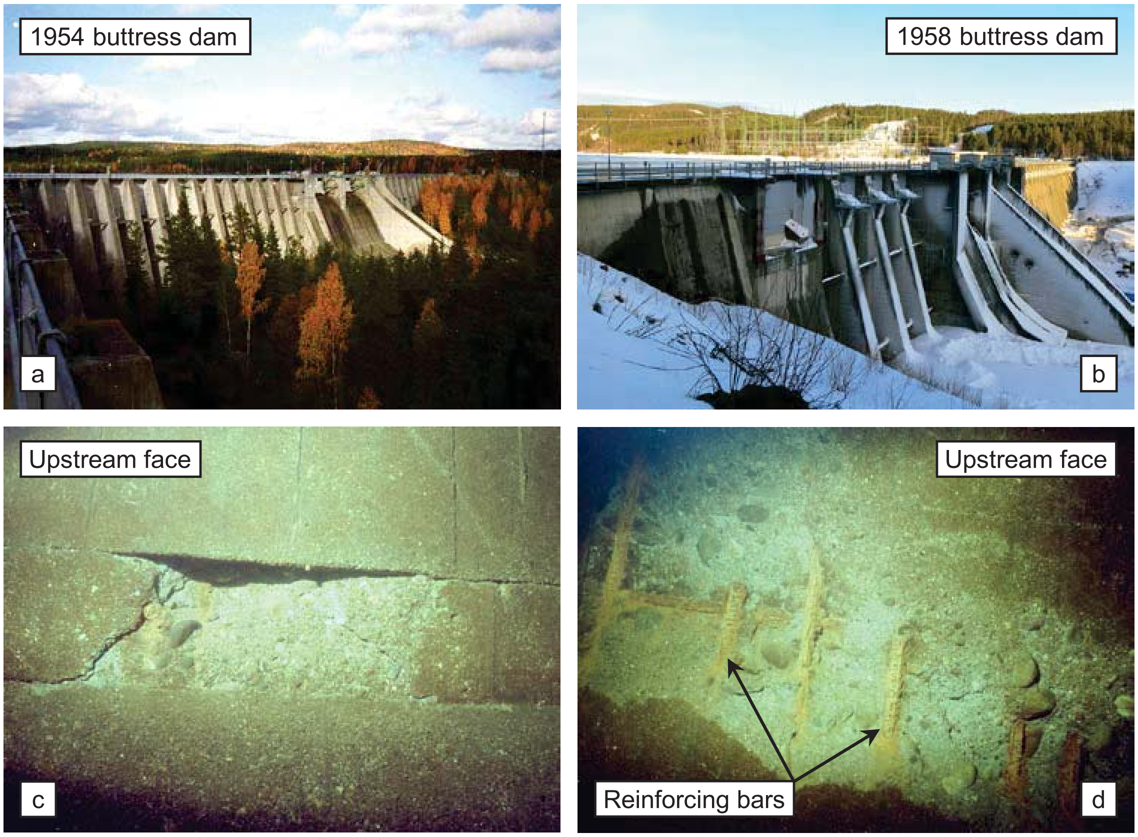

Figure 2-9. Two of the largest concrete dams in Sweden (a–b). After less than 40 years in service, areas of concrete spalling on the upstream face were discovered (c–d). Photos provided by Uniper.

In the case of the 1958 dam, cracks developed in the lower part of the flat slab after completion. According to Fahlén and Näslund (1991), the amount of cracks was significantly smaller in comparison to the 1954 dam. A few observations of concrete spalling were also made on the upstream face. In spite of a similar structural design, the choices of cement and compaction method are differences that may have contributed to the greater amount of damage to the 1954 dam.

Eriksson (1994) reported that up to 300 mm thick ice coatings were formed on the upstream face of the 1954 dam in winter. The formation of ice was confirmed by temperature measurements on the upstream face at 18 m depth. The measured temperature fell below 0 °C on more than one occasion during winter. In the early 1990s, both dams were rehabilitated and provided with heat insulating walls on the downstream side to prevent the flat slab from freezing.

Example 2

Construction work of the arch dam in Figure 2-10 (a) began in 1941 and the power plant was commissioned in 1944. The crest length of the arch is about 33 m and the height is 8 m. The thickness of the arch dam is approximately 350 mm. Neither the cement used nor the w/c-ratio of the concrete are known to the author.

Spalling of concrete was observed on the upstream and downstream face in the late 1960s. The greater part of the damage to the upstream face was found on the lower part of the dam (Figure 2-10 b). In some cases, divers were able to remove loose pieces of concrete up to a depth of 150 mm.

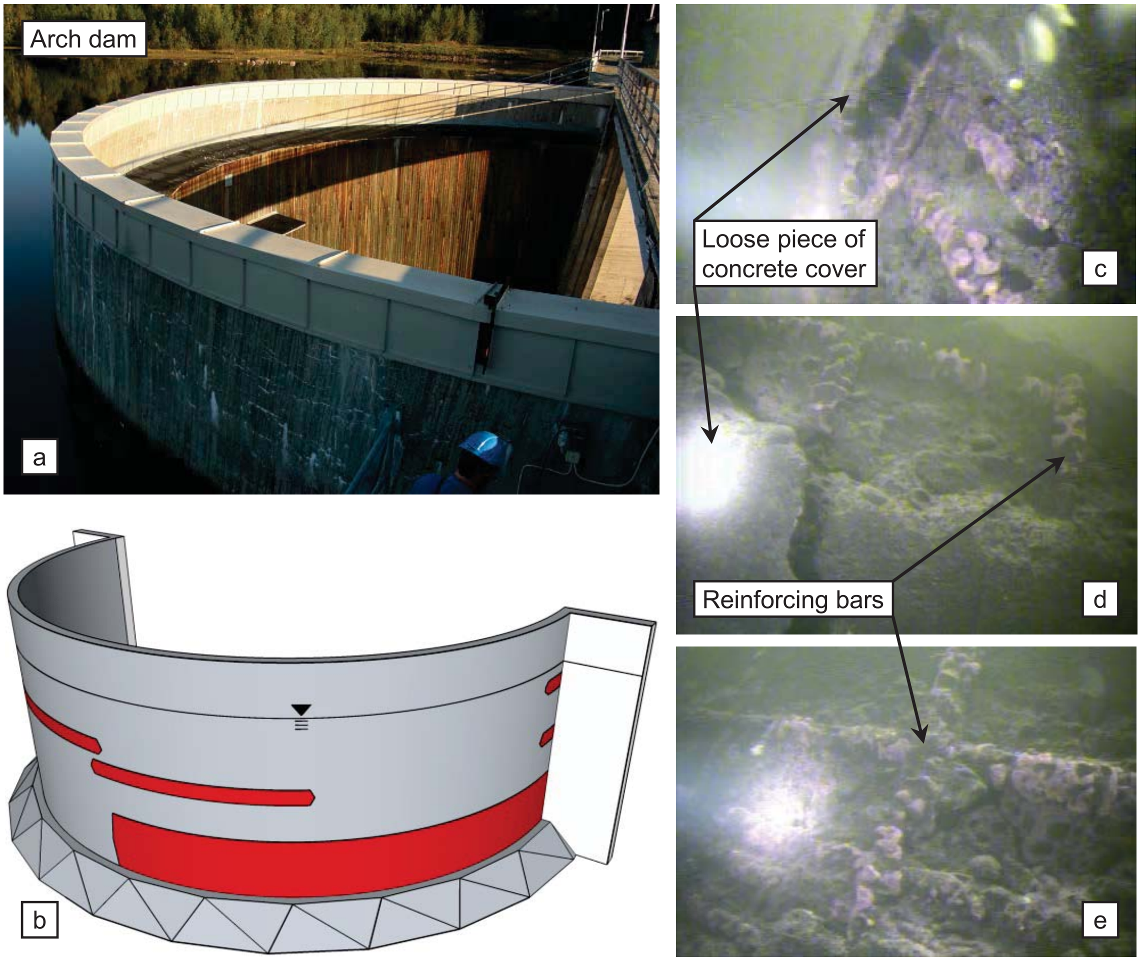

Figure 2-10. The greater part of the damage to the arch dam (a) was found on the lower part of the dam (b). Photos (c–e) show corroding reinforcing steel and loose pieces of concrete on the upstream face of the dam. Photos provided by Skellefteå Kraft AB.

The downstream face was immediately repaired, whereas the upstream face was left as found. Instead, a new arch (350 mm thick) was cast against the existing arch on the downstream side. To prevent further freezing of the old and new arches, the dam was provided with a heat insulating wall on the downstream side.

Photos taken during a recent diver inspection show the extent of damage to the upstream face (Figure 2-10 c–e). The concrete cover is missing in several places and corroding steel reinforcing bars are visible.

Example 3

Spalling of concrete was also observed on a buttress dam built in the early 1940s. The crest length of the dam is about 51 m and the maximum height is 9 m (Figure 2-11 a). The thickness of the flat slab is approximately 400 mm. Neither the cement used nor the w/c-ratio of the concrete are known to the author.

In some places on the downstream face, the reinforcing steel bars were exposed due to concrete spalling (Figure 2-11 b). The concrete in the damaged areas was wet due to water leakage through cracks in the flat slab just above the damaged areas. No action had been taken to repair the dam.

In April 2011, a hole appeared in the flat slab in early spring. The size of the hole was approximately 0.8 m in width and 1.2 m in height (Figure 2-11 c–e). All loose pieces of concrete were flushed away by the water escaping through the hole. Afterwards, only the reinforcing steel bars were seen bridging the hole.

Remarks

It can be assumed that the thin concrete dams have been frozen during the winter since they were not provided with heat insulating walls on the downstream side during construction. This assumption is confirmed by the observation of an ice coating on the upstream face far below the maximum water level of the 1954 dam. Moreover, it has to be assumed that the risk of frost damage is imminent when concrete of presumably high saturation levels is subjected to freezing.

In addition to these three examples of damaged dams, there are likely more thin concrete dams and other thin water retaining concrete structures with similar damage around the world. In order to understand the deterioration processes of thin water retaining concrete structures subjected to freezing, there is a need to determine the conditions under which spalling of concrete can occur.

Figure 2-11. A severely damaged buttress dam (a). Concrete cover missing in some places in the vicinity of water leakage through cracks on the downstream face (b). A hole appeared in the flat slab in another place and water escaped flushing away loose pieces of concrete (c–e). Only the reinforcing steel was left. Photos provided by Fortum AB.

3 Concrete properties

The basics of cement hydration, moisture fixation, water transport and frost-induced deterioration of concrete will be addressed in the following sections to enhance the understanding of the complexity of concrete. Moreover, the effects of interactions between multiple degradation mechanisms will also be addressed.

3.1 Physical properties of concrete

3.1.1 Hydration of cement

Chemical reactions are initiated on the surface of the cement grains when water is added. The chemical reaction between cement and water is known as hydration. During the hydration of Portland cement, heat is generated and different compositions of calcium silicate hydrates (C-S-H), calcium aluminium hydrates (C_3A), calcium aluminium iron hydrates (C_4AF) and calcium hydroxide (CH) are formed around the cement grains. The hydration products were collectively called cement gel by Powers and Brownyard (1948). The total volume of space between the particles of cement gel is called gel porosity.

In fresh concrete, the space between the cement grains is filled with water. During the hydration of cement, water is chemically bound to the hydration products. The space between the unhydrated parts of the cement grains is gradually filled with cement gel. Upon complete hydration in concrete mixes with a w/c-ratio of about 0.4, all space between the cement grains is theoretically filled with cement gel.

In concrete mixes with a w/c-ratio below 0.4, the theoretical volume of the cement gel formed upon complete hydration exceeds the volume of space between the cement grains. Consequently, particles of unhydrated cement remain in the concrete. In concrete with a w/c-ratio above 0.4, the volume of cement gel is not enough to fill all space between the cement grains. The unfilled space between the particles of cement gel is known as capillary porosity.

3.1.2 Types of voids in concrete

Different types of voids are formed during placement, compaction and hardening of concrete. The gel porosity mentioned previously is composed of a large number of gel pores. According to Powers (1962), the gel pore size ranges between 14 and 28 Å. The capillary porosity is composed of open and closed capillary pores of sizes smaller than 10 000 Å (0.001 mm). The average size of the capillary pores decreases with decreasing w/c-ratio.

Air is entrapped in concrete during mixing operations. These air voids are called compaction voids and are normally larger than 1 mm in size. Air entraining agents can be used to create artificial air voids in order to improve the frost resistance of concrete. According to Fagerlund (2002), the ideal sizes of entrained air voids range between 0.01 and 0.2 mm.

3.1.3 Moisture fixation in concrete

In cementitious materials such as cement paste, mortars and concrete, water can be physically and chemically bound to the material. Chemically bound water is water bound in the cement gel, whereas physically bound water is water bound to the surface of the pores through adsorption of water molecules or through surface tension effects causing capillary condensation. Chemically bound water is usually referred to as non-evaporable water, while physically bound water is referred to as evaporable water. Evaporable water is lost by drying at +105 °C, while non-evaporable water is lost at drying above +105 °C.

Adsorbed water is water molecules bound to the pore surface mostly by van der Waals forces. The amount of adsorbed water depends on the relative humidity and temperature. Additional molecule layers are adsorbed with increasing relative humidity and the molecule layers are known as adsorbate. As the thickness of the adsorbate increases with increasing relative humidity, curved water surfaces (menisci) are formed in small pores. By then, additional water molecules are condensed on the water surfaces at a given relative humidity, in a phenomenon known as capillary condensation. If the relative humidity continues to increase, capillary condensation also takes place in larger pores.

3.1.4 Saturation levels in concrete

The water content of concrete can be determined within the hygroscopic, capillary and over-capillary range. Sorption isotherms are often used to describe the relationship between physically bound water and the relative humidity (RH) of ambient air in the hygroscopic range (0–98 % RH) at a given temperature. The relative humidity of air is expressed by the formula:

$$\varphi = \frac{v}{v_s} \tag{1}$$

where v is the water vapour content and v_s the saturated water vapour content at a given temperature. Above the hygroscopic range, the water content may continue to increase due to capillary suction of water from external sources. However, air voids and compaction voids are generally not filled by capillary suction. Fagerlund (2006) suggested that absorption of water above the capillary saturation level continues due to dissolution of entrapped air in compaction voids and air voids. Figure 3-1 shows an absorption isotherm completed with the limits between the hygroscopic, capillary and over-capillary range.

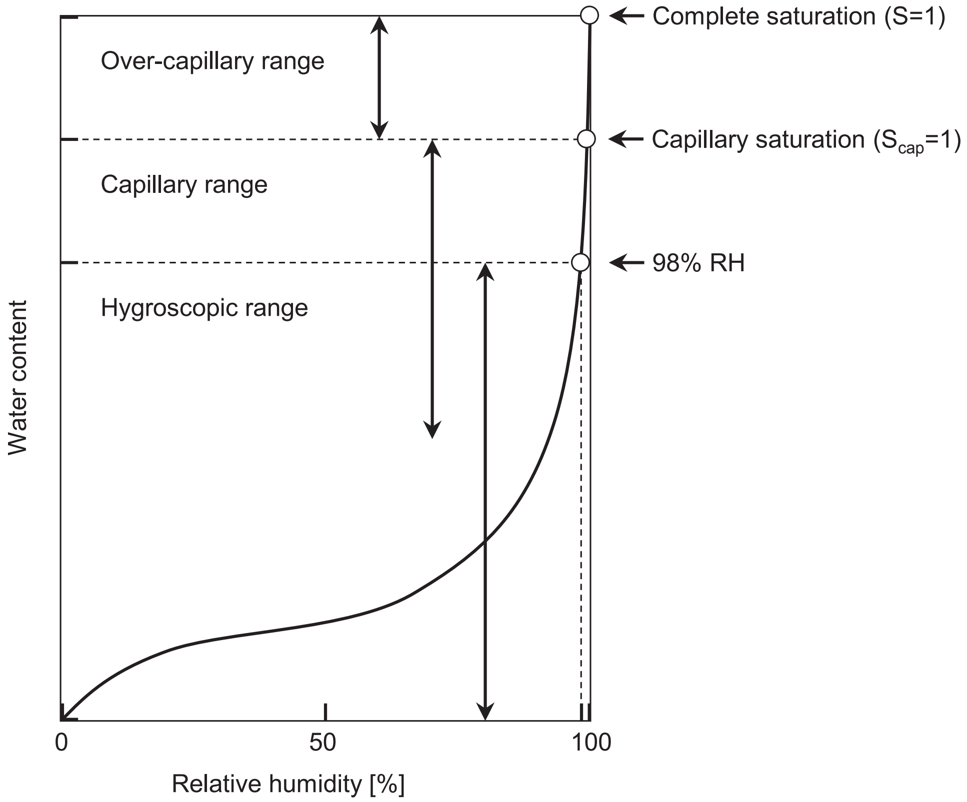

Figure 3-1. Absorption isotherm completed with the moisture ranges. Graph from Fagerlund (2006).

Above the hygroscopic range but within the capillary range, the water content of concrete can be expressed as the degree of capillary saturation (S_{cap}):

$$S_{cap} = \frac{m_{wet} - m_{105}}{m_{cap} - m_{105}} \quad (2)$$

where m_{wet} is the mass of the sample in the wet state, m_{cap} is the mass at capillary saturation and m_{105} is the mass in the dry state. Above the capillary range, the water content of concrete can be expressed as the degree of saturation (S):

$$S = \frac{m_{wet} - m_{105}}{m_{sat} - m_{105}} \tag{3}$$

where m_{wet} is the mass of the sample in the wet state, m_{sat} is the mass after saturation and m_{105} is the mass in the dry state. In this thesis, the expression 'saturation level' will be used to refer to the degree of saturation in concrete.

3.1.5 Water transport in concrete

Water transport phenomena in concrete can be divided into categories of diffusion, liquid and saturated flow. Diffusion of water molecules is driven by the difference in water vapour content at isothermal conditions, as water molecules move towards lower vapour content. The vapour flow (J_{v}) can be described by Fick's first law:

$$J_v = -\delta_v \frac{\partial v}{\partial x} \tag{4}$$

where δ_{v} is the vapour diffusion coefficient, v is the water vapour content and x is the distance over which diffusion occurs. Liquid flow (J_{l}) driven by capillary forces can be described as:

$$J_l = -D_l \frac{\partial P_l}{\partial x} \tag{5}$$

where the transport coefficient D_{l} is a function of the pore water pressure P_{l} while x is the distance over which liquid flow occurs. The pore water pressure (P_{l}) is determined by Laplace's law:

$$P_l = P_0 - \frac{2 \cdot \sigma \cdot \cos\theta}{r} \tag{6}$$

where P_0 is the atmospheric pressure, σ is the surface tension, θ is the contact angle between water and solid, and r is the pore radius. Janz (2000) stated that there is a lack of knowledge about water transport in the over-capillary range, despite the fact that many durability problems occur at high saturation levels.

Water can also be pushed into concrete structures subjected to hydrostatic pressure on one side and atmospheric pressure on the other side. Saturated flow (J_s) through concrete can be described by Darcy's law:

$$J_s = -\frac{k_p}{\eta}\frac{\partial P_h}{\partial x} \tag{7}$$

where k_p is the permeability coefficient, P_h is the hydrostatic pressure, η is the dynamic viscosity and x is the distance over which saturated flow occurs.

The flow of water through a concrete dam subjected to hydrostatic pressure is difficult to describe mathematically. One reason for this is that it is difficult to distinguish saturated flow (J_s) from liquid flow (J_l) and liquid flow from vapour flow (J_v). Another reason is that the different types of water flows overlap each other and the driving potentials also differ. Figure 3-2 presents a conceptual model of the water flow through a concrete dam, partly based on Hedenblad (1994).

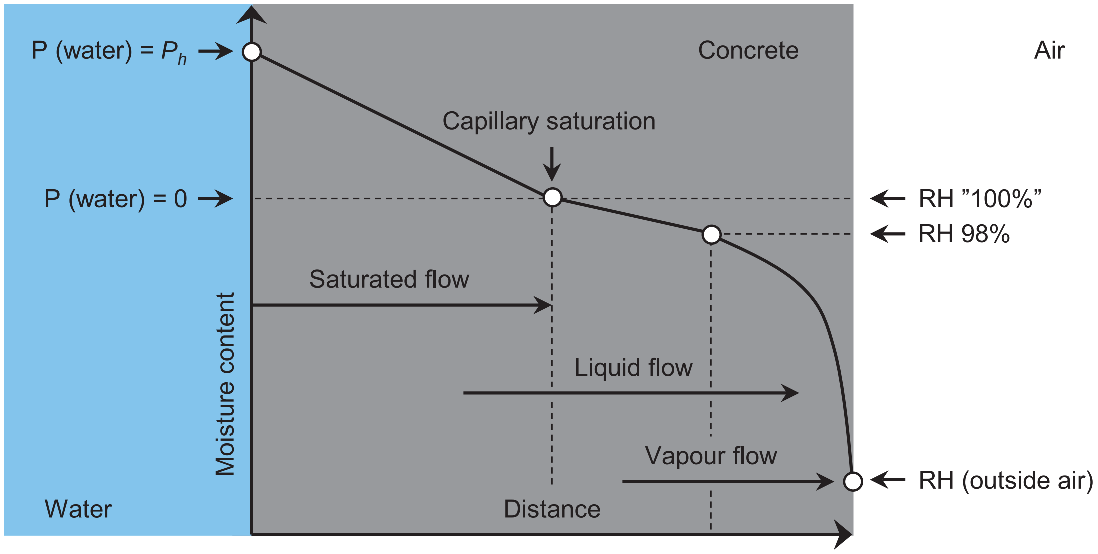

Figure 3-2. A conceptual model of water transport through a concrete dam. The driving potential for water flow (saturated flow) close to the upstream face of the dam is the hydrostatic pressure. At a certain distance from the upstream face, atmospheric pressure prevails and the water flow (liquid flow) is driven by capillary forces. Close to the downstream face of the dam, the water flow (vapour flow) is driven by the difference in vapour content.

In addition to hydrostatic pressure, pore water pressure and vapour content as driving potentials, varying temperature gradients can also affect the water transport and saturation levels in concrete structures. Wikström (2012) showed that concrete cylinders subjected to a temperature gradient in the range -5 °C to +10 °C absorbed more water at the hot side, which was in contact with water, than cylinders in isothermal conditions (+20 °C).

In another study, Sandström (2010) showed that concrete specimens subjected to alternating freeze-thaw conditions (-20 °C to +20 °C) absorbed more water than specimens in isothermal conditions (+18 °C). Based on the results of those two studies, it can be expected that absorption of water during freeze-thaw conditions leads to high saturation levels in concrete in hydraulic structures.

3.1.6 Permeability of concrete

The capillary porosity is continuous in young concrete. Hydration of cement increases the amount of cement gel, thus reducing the capillary porosity. Powers et al. (1959) reported that the capillary continuity is eventually blocked by cement gel if the w/c-ratio is less than 0.7. When the capillary continuity is blocked, capillary pores are formed. The w/c-ratio of the cement paste and the curing conditions determine the time until capillary discontinuity prevails.

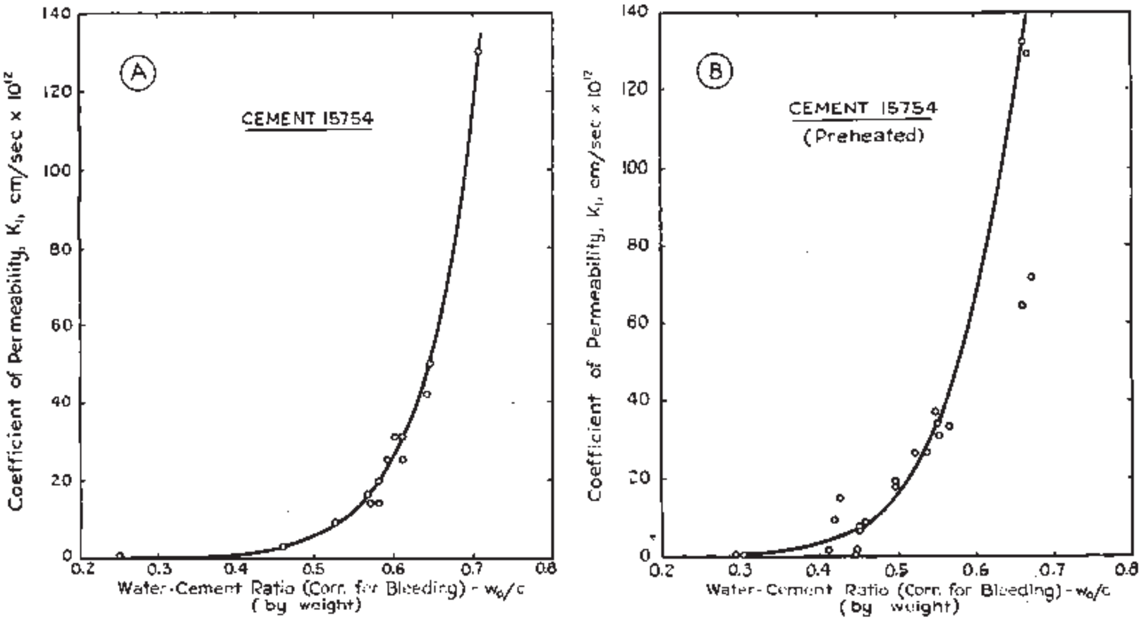

Figure 3-3. Relationships between hydraulic conductivity and w/c-ratio for mature cement paste. Graphs from Powers et al. (1954).

According to Powers et al. (1954), the overall permeability of concrete depends on the hydraulic conductivity of the cement paste, aggregate particles and the relative proportions of the two. Relationships between the hydraulic conductivity and the w/c-ratio for mature cement paste are shown in Figure 3-3.

The interfacial transition zone (ITZ) around aggregate particles is regarded by Leemann et al. (2006) as another key feature for the transport properties of concrete. Scrivener and Nemati (1996) showed that the cement paste in the ITZ has a significantly higher porosity than the bulk cement paste. The increase in porosity is believed to affect the transport properties of concrete.

The overall permeability of concrete can be increased locally by fissures under aggregate particles and reinforcing steel bars due to bleeding and delayed setting of the concrete. The permeability of concrete may have a large impact on the durability of concrete structures and especially of hydraulic structures subjected to hydrostatic pressure, frost action and aggressive agents.

As mentioned previously, gel pores, capillary pores, compaction voids and air voids are all present in concrete. The volume of these voids determines the total porosity (V_{pt}) of concrete. However, not all voids in concrete are connected to other voids. Therefore, voids without connection to other voids have no impact on either the overall permeability of concrete or the properties of concrete during wetting and drying. The volume of voids in contact with other voids, known as open porosity (V_{po}), is given by the formula:

$$V_{po} = \frac{m_{sat} - m_{105}}{m_{sat} - m_{sub}} \tag{8}$$

where m_{sat} is the mass of the sample at saturation, m_{105} is the mass of the sample in the dry state and m_{sub} is the mass of the saturated sample submerged in water.

3.2 Frost resistance of concrete

3.2.1 Frost degradation mechanisms

Powers (1945) stated that hardened concrete subjected to frost action can be damaged either by scaling or internal damage. Scaling deteriorates the surface, whereas internal damage lowers the compressive and tensile strength of concrete. Powers proposed the hydraulic pressure theory in order to explain the mechanism of frost damage. The theory was based on the fact that water expands 9 % upon freezing. When excess water is forced out of the capillary pores, a hydraulic pressure gradient is created by the flow resistance in the surrounding cement paste. Frost damage occurs if this pressure gets too high.

As Powers presented his theory regarding frost damage to concrete, Collins (1944) proposed a macroscopic ice lens growth theory to explain field observations of concrete damage in England 1941–1942. The macroscopic ice lens growth theory was based on the theory of frost heave in soils. Taber (1930) had shown that macroscopic ice lens growth may occur in frost susceptible soils subjected to long periods of freezing temperatures. Collins showed that poor quality concrete can also be damaged in the same way.

According to Powers and Brownyard (1948), water in cement paste has different freezing temperatures in pores of different sizes. Nucleation of ice crystals becomes more difficult as the pore size decreases. When water freezes in large capillary pores, water in small capillary pores and gel pores remains unfrozen. The amount of freezable water increases with decreasing temperatures. Powers and Helmuth (1953) proposed the microscopic ice lens growth theory, based in part on the fact that the freezing temperature of water in cement paste depends on the pore size. Ice crystals in large capillary pores attract water from the gel and smaller capillary pores. Consequently, water moves into the large capillary pores and causes the ice crystals to grow to microscopic ice lenses.

Throughout the years, additional theories have been suggested to explain frost damage, such as the osmotic pressure theory and the glue spall theory. Apart from the theories of frost damage mechanisms, Fagerlund (1977) showed that frost damage inevitably occurs if the water content exceeds the critical degree of saturation (S_{cr}) corresponding to a certain temperature. For ordinary concrete mixes, S_{cr} ranges from 0.75 to 0.90.

The mechanisms of frost damage are further described in Paper I. The theories of frost heave in soils and macroscopic ice lens growth in bedrock and hardened concrete are presented in Paper VII.

3.2.2 Frost resistance

When air entraining agents are used in concrete, the frost resistance improves. Artificially created air voids are not filled with water by capillary forces and therefore remain filled with air. According to Powers (1949), air voids provide empty spaces within concrete where ice can form without exerting pressure on the pore walls. Hence, capillary saturation can be obtained in air-entrained concrete without exceeding the critical degree of saturation (S_{cr}).

Powers (1954) stated that the frost resistance of concrete is determined by the combined effects of the volume of entrained air, pore size distribution and spacing factor. The spacing factor is an estimate of the longest distance to an air void surface in cement paste. Tange Hasholt (2014) suggested that the total surface area of air voids could be a better measurement parameter than the spacing factor when linking air void characteristics to the salt-frost resistance of concrete. The reason for this is that the total surface area of air voids expresses the likelihood that a capillary pore is connected to an air void, while the spacing factor expresses the likelihood that the capillary pore is located in the vicinity of an air void. The basics of frost resistance of concrete are further described in Paper I.

3.2.3 Reduced frost resistance

Concrete structures submerged or partially submerged in water eventually reach capillary saturation. Fagerlund (2006) reported that concrete absorbs water in the over-capillary range due to dissolution of entrapped air in compaction and air voids. The diffusion rate of air out of the voids and eventually out of the material determines the time (t_{cr}) until the critical degree of saturation (S_{cr}) prevails (Figure 3-4). Furthermore, Fagerlund (1993) stated that the solubility of air is proportional to the hydrostatic pressure. It can thus be assumed that the rate at which the air voids fill with water increases with increasing hydrostatic pressure.

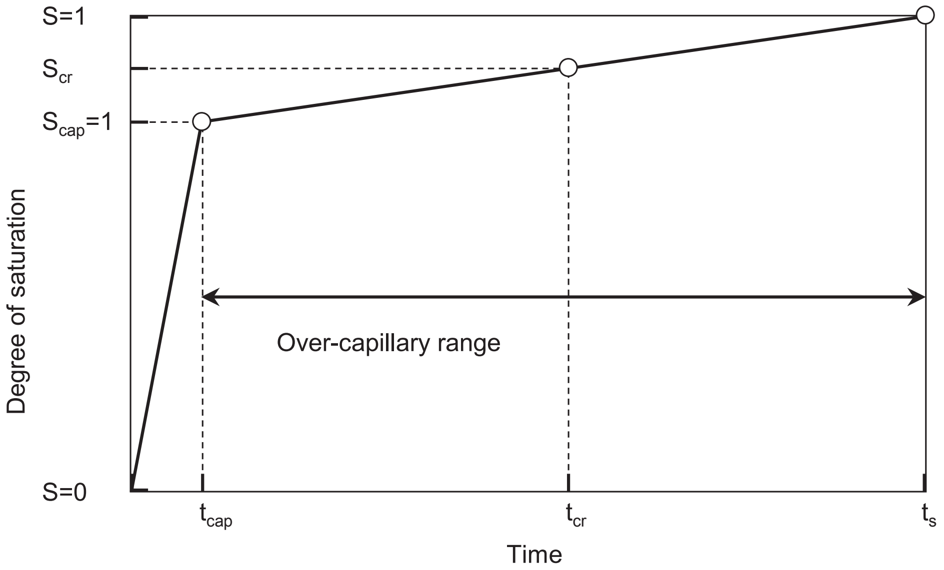

Figure 3-4. Water absorption of concrete as a function of time. The critical degree of saturation (S_{cr}) prevails at the critical time (t_{cr}).

To highlight the importance of the water content on the risk of frost damage, Fridh (2005) stated that the water content has a greater impact on the frost resistance of concrete than do the w/c-ratio and air content. In concrete with a high w/c-ratio and porosity, a certain amount of water may not be sufficient to cause frost damage upon freezing, whereas the same amount of water may cause damage in concrete with low w/c-ratio and porosity.

3.3 Interacting degradation mechanisms

3.3.1 Synergy

Even though the resistance to a certain degradation mechanism may be satisfactory for a given concrete sample, the effects of additional mechanisms may significantly reduce the resistance to the first mechanism. Synergy is defined as the interaction of two or more elements, which together produce an effect greater than the sum of their individual effects. Hence, synergy may occur when multiple degradation mechanisms interact.

As stated in Section 2.3, hydraulic structures in contact with fresh water in cold regions are generally subjected to leaching and abrasion in addition to frost action. Therefore, the basics of leaching and abrasion will be described in the following sections. It is, however, reasonable to assume that other degradation mechanisms also may cause deterioration of concrete in hydraulic structures. Deterioration of concrete due to aggressive agents, extreme loads, seasonal temperature variations and chemical reactions between cement and an aggregate causing swelling is outside the scope of this thesis.

3.3.2 Leaching

It is well known that cementitious materials are not thermodynamically stable when in contact with soft water. Concentration gradients between the external water and the pore solution of concrete cause diffusion of dissolved ions out of the concrete that leads to dissolution of hydration products (Ekström, 2003). The hydration products of hardened Portland cement paste are soluble in water to varying degrees. The process of dissolution and diffusion of calcium compounds is known as lime leaching, or simply leaching.

The most soluble hydration product in cement paste is calcium hydroxide (CH). Calcium is also dissolved from the other hydration products, such as ettringite, monosulphate and C-S-H. However, as long as there is CH present, calcium from the other hydration products is dissolved to a much lesser extent.

Bertron et al. (2007) stated that leaching increases the porosity and reduces the mechanical strength of cement paste. Carde and François (1999) reported that leaching of CH increases the macroporosity whereas leaching of C-S-H increases the microporosity. Moreover, Haga et al. (2005) stated that pores 0.2 µm in size or larger are primarily affected by leaching of CH. Hence, it can be assumed that leaching of CH increases the capillary porosity of cement paste. The rate at which calcium compounds are dissolved in water depends mostly on the aggressiveness of the water and the permeability of concrete.

The diffusion kinetics of calcium can be described by Fick's law relating the calcium-leached thickness to the square root of time (Adenot and Buil, 1992). Leaching of the surface is therefore rapid at the beginning of this process. Ekström (2003) showed that calcium leaching was greater near the surface compared to deeper regions of a specimen, which had been stored in a tank containing deionised water for about two years. Moreover, as the thickness of the calcium-leached layer increases, the leaching rate decreases. The calcium-depleted surface layer may thereafter act as a protection barrier against further diffusion of dissolved components of the cement paste.

The basics of dissolution and diffusion of hydration products due to leaching of concrete by soft water and acidic solutions are further described in Paper III.

3.3.3 Erosion

Flowing water may cause erosion of concrete surfaces. Spillways are an example of hydro power structures that are subjected to erosion by water and sediments carried by the water. Ice floes and driftwood may also cause abrasive wear of the concrete surfaces at the waterline of hydraulic structures.

Huovinen (1993) reported that marine concrete structures in arctic sea regions are subjected to heavy mechanical loads at the waterline due to drifting sea ice. The strength of concrete was found to have the greatest impact on the resistance to ice abrasion. Moreover, the use of supplementary cementitious materials, such as blast furnace slag and silica, improved the resistance to ice abrasion.

In another study, Møen et al. (2007) concluded that ice sliding against concrete structures causes more abrasion than ice crushing against the structures. Jacobsen et al. (2015) reported that particles released from the concrete surface can enhance abrasion as ice drags them along the surface. Water forced into surface defects such as cracks can also create pressure that further enhances crack growth.

3.4 Research questions

As reported in Chapter 2, the long-term performance and durability of concrete in water retaining parts of many Swedish hydro power structures depends on the resistance to leaching, frost action and abrasion. However, it is not fully known exactly how the concrete in these structures deteriorates and how the different degradation mechanisms interact. In addition, there are concerns about the long-term frost resistance of air-entrained concrete submerged or partially submerged in water for long periods of time.

With regard to the different environmental exposure conditions and the associated damage to concrete in hydro power structures (described in Sections 2.3 and 2.4), the uncertainty of how the concrete in those structures deteriorates has prompted the following four questions addressing the risk of frost-induced deterioration of concrete in hydro power structures and other hydraulic structures:

- Which degradation mechanisms are causing progressive deterioration of the concrete surface at the waterline of hydro power structures?

- Is there any risk of internal frost damage to concrete at and above the maximum water level of hydro power structures?

- What are the conditions for spalling of concrete in thin water retaining concrete structures subjected to long periods of freezing temperatures?

- How is the frost resistance of air-entrained concrete affected by long-term submersion in water?

4 Surface deterioration at the waterline

This chapter presents experimental studies performed to determine the causes of progressive deterioration of the concrete surface at the waterline of hydro power structures (Figure 2-6 a–d). Both laboratory-cast concrete and concrete from an existing dam were used in the studies. These studies are also presented in Paper I, Paper II, Paper III, Paper IV and Paper V.

4.1 Development of a new test method

Standardised test methods, such as ASTM C672, CDF and SS 13 72 44, have been developed to assess the freeze-thaw resistance of horizontal surfaces such as concrete roads and pavements. These methods were not considered appropriate for assessing the frost resistance of vertical concrete surfaces at the waterline of hydro power structures. Consequently, a new test method had to be developed.

This new test method makes it possible to subject concrete specimens to sub-zero temperatures in the presence of unfrozen water. As in reality, ice is formed on the specimens at and below the waterline during the freezing phase of the test. The design of the test setup and the 13-hour freeze-thaw cycles are described in Paper I. In this thesis, this new test method is termed the frost test.

As an initial study, two concrete mixes were produced to verify the test method; non-air-entrained concrete with a w/c-ratio of 0.65 and air-entrained concrete with a w/c-ratio of 0.45. A Portland-limestone cement (CEM II/A-LL 42.5 R) was used as the binder. The concrete with a w/c-ratio of 0.65 was expected to suffer superficial damage at the waterline, whereas the concrete with a w/c-ratio a 0.45 was not. During the test period, specimens of the concrete mixes were subjected to approximately 50 freeze-thaw cycles. In accordance with the actual system (Figure 2-3), a band of ice was formed at the waterline of the specimens during freezing.

At the end of the frost test, superficial damage was observed at the waterline of the concrete specimens with a w/c-ratio of 0.65, whereas the specimens with a w/c-ratio of 0.45 sustained no damage. Based on these results, the test method can be used to distinguish between frost resistant concrete and non-frost resistant concrete subjected to climatic conditions prevailing at the waterline of hydro power structures. The results of this initial study are detailed in Paper I.

4.2 Frost resistance of the concrete surface

Based on the experience gained during the development and verification phases of the frost test presented in Paper I, a second study was designed. At this time, it was decided to use the frost test to assess the risk of superficial damage to concrete mixes similar to those used during the Swedish hydro power development in the mid-20th century. The purpose of the study was to determine whether frost action can account for the surface deterioration at the waterline or not.

Concrete mixes with w/c-ratios of 0.54, 0.62 and 0.70 were produced and subjected to the frost test. The mix proportions were selected in accordance with handbooks and guidelines published by Kungliga Vattenfallsstyrelsen (1942) and (1945), Statens Vattenfallsverk (1956) and (1972) and Vattenbyggnadsbyrån (1943) and (1954). The air-entrained concrete mix with a w/c-ratio of 0.54 is typical for concrete used in hydro power structures during the 1950s and 1960s. The non-air entrained concrete mix with a w/c-ratio of 0.62 is typical for concrete used between 1930 and 1950. Non-air-entrained concrete mixes with a w/c-ratio up to 0.70 were occasionally used in structures not subjected to hydrostatic pressure. The production and preparation of the concrete specimens is described in Paper II.

Because the CEM I cements from Limhamn have been out of production since the late 1970s, a moderate heat and low alkaline Portland cement (CEM I 42.5 N MH/SR/LA) developed in the early 1980s was used in this study. The clinker phase composition of the cement is similar to that of the Limhamn Std cement, which together with the Limhamn LH cement was used for the construction of many large hydro power plants in Sweden between the 1930s and the 1970s.

In this study, two changes were made in the frost test procedure: (1) the test period was extended from four weeks to eight weeks, and (2) the freeze-thaw cycle was shortened by one hour to twelve hours, with 7.5 hours of freezing and 4.5 hours of thawing. Hence, the frost test consisted of 112 freeze-thaw cycles.

After the 112 freeze-thaw cycles, only minor damage to the surface was observed at and below the waterline of the non-air-entrained specimens with a w/c-ratio of 0.70. The damage was concentrated to a band 20–30 mm in width below the waterline (Figure 4-1 a). For the non-air-entrained specimens with a w/c-ratio of 0.62, minor damage to the concrete surface was observed at the waterline by the removal of small flakes of cement paste (Figure 4-1 b). The amount of damage varied somewhat between the specimens. No damage to the concrete surface below the waterline could be observed. For the air-entrained specimens with a w/c-ratio of 0.54, no damage could be observed on any of the specimens (Figure 4-1 c).

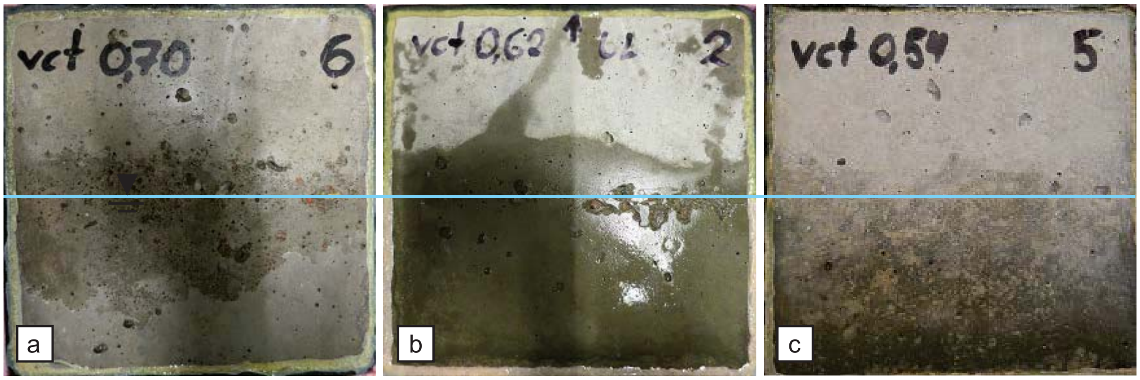

Figure 4-1. Minor damage occurred at the waterline of the non-air-entrained specimens with w/c-ratios of 0.70 (a) and 0.62 (b). No damage occurred to the air-entrained specimens with a w/c-ratio of 0.54 (c).

To compare the results from the frost test with a standardised test, the scaling resistance of the concrete mixes was determined according to the Swedish test method SS 13 72 44 (SIS, 2005). One set of specimens for each w/c-ratio was subjected to 56 freeze-thaw cycles in the presence of deionised water and another set to a 3 % NaCl solution. The standard states that the scaling resistance can be classified into four classes; *Very good*, *Good*, *Acceptable* and *Unacceptable*. *Very good* means the weight of scaled materials is less than 0.1 kg/m^2.

According to the results, the scaling resistance of the cut surface in the presence of deionised water was *Very good* for the three concrete mixes. When the cut surface was exposed to the salt solution, only the air-entrained concrete mix with a w/c-ratio of 0.54 was classified as *Very good*. The non-air-entrained concrete mix with a w/c-ratio of 0.62 was classified as *Acceptable* (< 1.0 kg/m^2) and the non-air-entrained concrete mix with a w/c-ratio of 0.70 as *Unacceptable*. The results of this study are further detailed in Paper II.

Freezing in the presence of deionised water did not cause scaling of non-air-entrained concrete with w/c-ratios of 0.70 and 0.62, nor did freezing in the presence of the salt solution cause scaling of air-entrained concrete with a w/c-ratio of 0.54. The latter result could be explained by the fact that concrete is generally protected against the destructive forces of frost action by a carefully designed air pore system. However, the result does not match the observations of superficial damage to hydro power structures built with air-entrained concrete with w/c-ratios in the range of 0.50 to 0.55. Based on the results of this study, frost action cannot solely account for the surface deterioration at the waterline of Swedish hydro power structures.

4.3 Interacting degradation mechanisms

The previous study on the frost resistance of the concrete surface was unable to provide a satisfactory explanation of how surface deterioration occurs at the waterline. In addition to frost action, concrete at the waterline of hydro power structures is exposed to river water and abrasive wear by ice floes and driftwood. As shown by Table 2-1 in Section 2.3, the water in many of the major rivers in Sweden can be regarded as soft and thus cause leaching of calcium compounds. Bertron et al. (2007) stated that leaching increases the porosity and reduces the mechanical strength of the cement paste. Hence, the ability to resist frost action and abrasion may decrease as a consequence of surface leaching.

Hassanzadeh (2010) has suggested that interactions between multiple degradation mechanisms may cause progressive deterioration of the concrete surface at the waterline. However, he could not point out the dominating mechanism.

To assess the effects of interactions between multiple degradation mechanisms, a third study was designed as described in Paper III. Again, the non-air-entrained concrete mix with a w/c-ratio of 0.62 and the air-entrained concrete with a w/c-ratio of 0.54 were used in the experimental tests. Specimens were subjected to different combinations of leaching (L), frost action (F) and abrasion (A):

▪ (F)	Frost action
▪ (F+A)	Frost action + Abrasion
▪ (L+A)	Leaching + Abrasion
▪ (L+F)	Leaching + Frost action
▪ (L+F+A)	Leaching + Frost action + Abrasion

Leaching of calcium compounds from the concrete surface was accelerated by submerging the specimens in deionised water at pH 4 for one week. With the intent to easily subject the specimens to seven freeze-thaw cycles in the presence of deionised water, the Swedish test method SS 13 72 44 was used (SIS, 2005). Abrasive wear of the concrete surface was caused by steel brushes being brushed ten times back and forth. The effects of leaching, frost action and abrasion were quantified as the weight of loose materials collected from the concrete surface. The designs of the test setup and the test procedure are further described in Paper III.

For the air-entrained specimens with a w/c-ratio of 0.54, no loose particles were collected from the specimens subjected to frost action (F), nor from the specimens subjected to a combination of frost action followed by abrasion (F+A). The amount of loose materials was significantly increased for the specimens subjected to leaching in water at pH 4 prior to abrasion (L+A), particularly for the specimens subjected to leaching and frost action (L+F). However, the greatest amount of loose material was collected from the specimens subjected to all three degradation mechanisms (L+F+A). Similar behaviour was obtained for the non-air-entrained specimens with a w/c-ratio of 0.62. Of note, the effects of leaching on the frost resistance were even greater in this case.

Synergy was defined previously in Section 3.3 as the interaction of two or more elements, which together produce an effect greater than the sum of their individual effects. In this study, the accumulated weight loss of the specimens subjected to all three degradation mechanisms (L+F+A) was greater than the sum of the accumulated weight loss of the specimens subjected to frost action (F) together with the specimens subjected to leaching and abrasion (L+A). Furthermore, the weight loss of specimens subjected to all three mechanisms (L+F+A) also exceeded the sum of (L+F)+(A). These differences in weight loss confirm that synergy occurs when the concrete surface is subjected to all three degradation mechanisms. The results on the interactions between leaching, frost action and abrasion on the surface deterioration of concrete are further detailed in Paper III.

The final appearance of the concrete surface of specimens subjected to the three degradation mechanisms is shown in Figure 4-2. In accordance with the measured weight losses, the surface of the specimens subjected to frost action (F) remained intact, whereas the surface of the specimens subjected to all three degradation mechanisms (L+F+A) was progressively deteriorated. The amount of damage to the concrete surface was greater for the non-air-entrained concrete with a w/c-ratio of 0.62 compared to the air-entrained concrete with a w/c-ratio of 0.54.

Based on the results, a possible scenario of concrete deterioration at the waterline begins with leaching of the surface during the snowmelt and summer periods. It is reasonable to assume that the concrete surface becomes susceptible to frost action and abrasion during this time. In this case, the surface layer can be damaged during the following winter and later removed by abrasion. The process then begins anew and surface deterioration continues. In order to verify this scenario of concrete deterioration in reality, it is necessary to determine whether leaching of the concrete surface also occurs in existing structures.

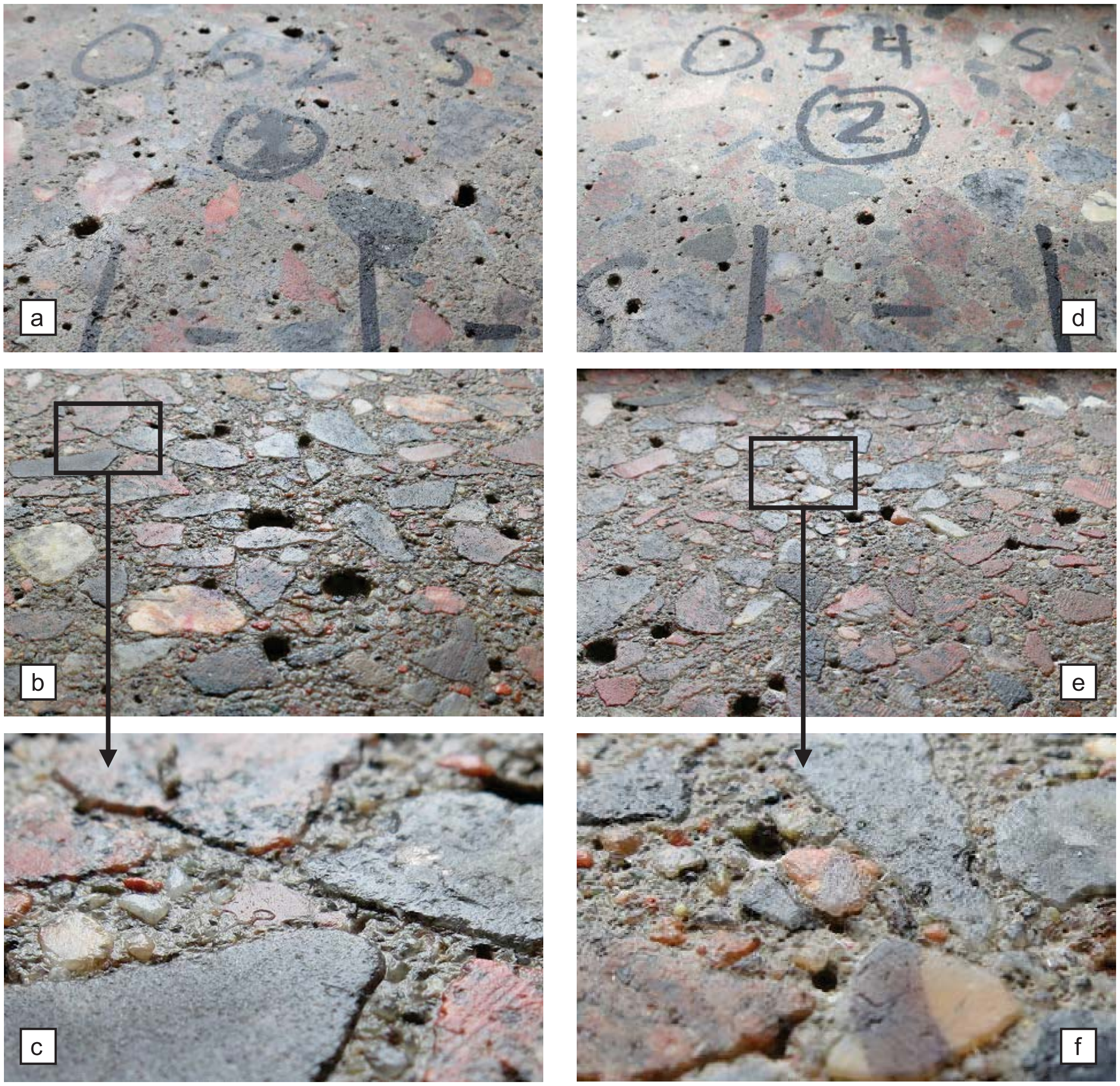

Figure 4-2. Cut face (w/c-ratio 0.62) subjected to (F) in (a) compared to the cut face subjected to (L+F+A) in (b). Enlargement of the area marked by the rectangle in (c). Cut face (w/c-ratio 0.54) subjected to (F) in (d) compared to the cut face subjected to (L+F+A) in (e). Enlargement of the area marked by the rectangle in (f).

4.4 Effects of surface leaching

In previous studies on the effects of interacting degradation mechanisms, leaching was shown to significantly amplify the effects of frost action and abrasion for both non-air-entrained concrete (w/c-ratio of 0.62) and air-entrained concrete (0.54). However, no definite conclusions could be drawn with regard to existing structures based on these prior results.

To address the question of how long-term exposure to river water affects the chemical and mineralogical composition of cement paste, concrete cylinders were taken at four different vertical locations on the concrete dam (Figure 2-9 b) in November 2013. The four locations were above the normal water level (-1 m), at the normal water level (0 m) and far below the normal water level (10.5 and 18.5 m). The w/c-ratio of the air-entrained concrete was approximately 0.50.

Chemical and mineralogical modifications of the cement paste related to the alteration of concrete were analysed with an electron microprobe (EPMA), an X-ray diffractometer (XRD), a scanning electron microscope (SEM) combined with an energy dispersive X-ray spectrometer (EDS) and a thermogravimetric analyser (TGA). Preparation of the specimens for analysis is described in Paper IV.

The analyses showed that exposure to the soft water of the river Ångermanälven leads to chemical and mineralogical zonation of the cement paste. Four zones parallel to the upstream face were observed in the concrete cylinder taken at the normal water level, whereas five zones were observed in the cylinders from the depths of 10.5 and 18.5 m. Hence, exposure to the river water leads to dissolution, re-precipitation and diffusion of hydration products of the cement paste.

Figure 4-3 presents the chemical composition of the cement paste according to the distance to the upstream face at a depth of 10.5 m. Major changes to the chemical composition could be noted only in the outermost 7.5–8.5 mm of the upstream face. The innermost Zone 1, which is part of the sound zone, has a stable chemical composition from the inside to the limit with Zone 2.

Zone 2 is a transition zone where dissolution of calcium hydroxide (CH) occurs. Partial decalcification of C-S-H occurs also in this zone, as well as precipitation of non-expansive secondary ettringite. In Zone 3, the chemical composition is rather stable whereas Zone 4 is characterised as a second transition zone, where a decrease in the calcium content is concurrent with an increase in the magnesium content. Near the limit of Zone 5, the compactness of the cement paste is significantly reduced, thus making it porous and fragile. In Zone 5, the magnesium content increases remarkably and the zone takes the form of a shell due to the greater compactness of the cement paste. The results on the chemical and mineralogical changes of the cement paste are further detailed in Paper IV.

In concrete at the waterline, Zone 4 is thin and Zone 5 does not exist. One possible explanation for this is that concrete at the waterline is subjected to frost action and abrasion during the winter and spring. Based on the fact that leaching significantly reduces the compactness of cement paste, it can be assumed that the calcium-depleted surface layer is susceptible to frost action.

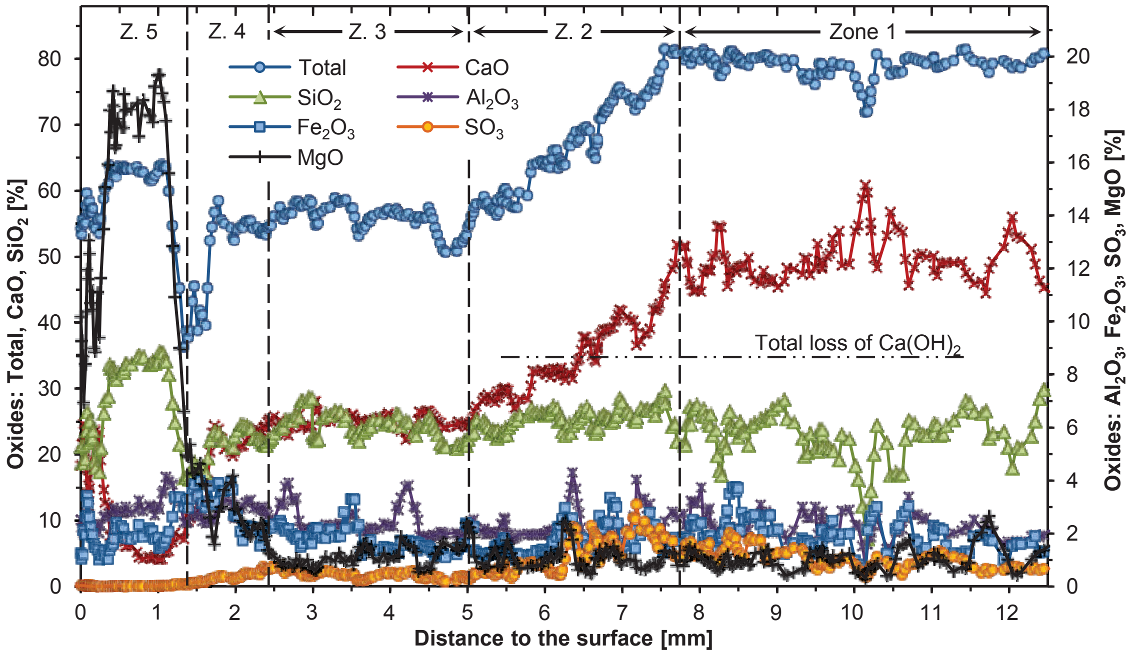

Figure 4-3. Chemical composition of cement paste in concrete at a depth of 10.5 m according to the distance to the upstream face.

The effects of surface leaching on the frost resistance of concrete were assessed by subjecting concrete specimens from the dam (Figure 2-9 b) to freeze-thaw tests according to SS 13 72 44 (SIS, 2005). Both the upstream face and a cut face from the four vertically different locations on the dam were subjected to these tests. The cut face was positioned at least 50 mm from the upstream face. The specimens were subjected to 112 freeze-thaw cycles in the presence of deionised water and then to another 112 cycles in the presence of a 3 % NaCl solution.

It was noted that Zone 4 and 5 were easily removed due to freezing and thawing in the presence of deionised water. Most of Zone 3 was eventually removed during these initial 112 freeze-thaw cycles. The specimens were then kept for three months at a temperature of 20 °C and relative humidity of 65 % prior to the 112 freeze-thaw cycles in the presence of the 3 % NaCl solution. During these freeze-thaw cycles, the remaining part of Zone 3 and most of Zone 2 were removed. For concrete at a depth of 10.5 m, the very outermost part of Zone 1 was also removed.

The frost resistance of the cut face was *Very good* (scaled materials < 0.1 kg/m^2) for all specimens subjected to 224 freeze-thaw cycles. It should be noted that this included 112 freeze-thaw cycles in the presence of the 3 % NaCl solution. Hence, the unaltered concrete can be classified as frost resistant according to SS 13 72 44. The results on the freeze-thaw resistance are detailed in Paper V.

Since this chapter concerns surface deterioration of concrete at the waterline of existing hydro power structures, it is of considerable interest to be able to predict the service life of the concrete layer that covers the reinforcement. Regarding the concrete dam in Figure 2-9 (b), the rate of surface deterioration at the waterline can be estimated based on the results of the studies performed.

Paper IV presents measurements of the chemical composition of the cement paste at the waterline (0 m) according to the distance to the upstream face of the dam. It was shown that the outermost Zone 4 measured 230 µm in thickness in the month of November, just before winter set in. The freeze-thaw tests presented in Paper V showed that Zone 4 was easily removed during freeze-thaw cycles in the presence of deionised water. It can therefore be assumed that Zone 4 is removed every winter and then re-formed during the following summer period.

Given these assumptions, the rate of surface deterioration at the waterline of this particular dam can be estimated between 0.20 and 0.25 mm per year. It will thus take more than 200 years to remove the concrete cover under these conditions when the thickness is 50 mm. Careful analysis of the chemical composition of the cement paste can be used to predict the rate of surface deterioration of air-entrained concrete at the waterline of Swedish hydro power structures.

4.5 Discussion

This chapter presents the experimental studies performed to determine which degradation mechanisms are causing progressive deterioration of the concrete surface at the waterline of hydro power structures. As previously reported in Section 2.3, superficial damage of similar appearance can be observed on both the upstream and downstream side of hydro power structures in Sweden. The damage is evenly distributed along the waterline, thus indicating that the deterioration is generated by continuous processes rather than impacts from ice and driftwood.

In the studies presented previously, it was shown that freeze-thaw conditions similar to those prevailing at the waterline of hydro power structures cannot solely account for the damage observed on the structures built of air-entrained concrete with w/c-ratios of 0.50–0.55. It was thus concluded that surface deterioration at the waterline is not caused by a single degradation mechanism. Instead, it was assumed that surface deterioration of concrete along the waterline is caused by the combined effects of multiple degradation mechanisms.

In a study to determine the effects of interactions between leaching, frost action and abrasion, it was shown that leaching significantly amplifies the effects of frost action and abrasion on the rate of surface deterioration of air-entrained concrete with a w/c-ratio of 0.54 and non-air-entrained concrete with a w/c-ratio of 0.62. It was also shown that the amount of damage caused by the combined effects of the three degradation mechanisms exceeded the total amount of damage caused by the mechanisms separately, thus confirming that synergy occurs.

Based on chemical analysis of the water in some Swedish rivers, it was shown that the water in most rivers can be regarded as soft (Table 2-1). It is therefore reasonable to assume that long-term exposure to the river water causes leaching that may weaken the concrete surface to such an extent that it becomes susceptible to deterioration by other degradation mechanisms. Such an assumption is supported by the fact that leaching of calcium compounds increases the porosity and reduces the mechanical strength of cement paste (Bertron et al. 2007).

Moreover, Carde and François (1999) stated that leaching of CH increases the macroporosity of cement paste while leaching of C-S-H increases the microporosity. According to Powers (1962), the capillary porosity is attributed to pores of sizes smaller than 1 µm. Since Haga et al. (2005) reported that pores larger than 0.2 µm are mostly affected by leaching of CH, it is reasonable to assume that leaching of CH increases the capillary porosity of cement paste.

Microstructural studies of the cement paste in concrete originating from the 55-year old concrete dam (Figure 2-9 b) confirmed that long-term exposure to the river water causes dissolution and diffusion of CH out of the concrete. Moreover, the exposure to river water causes chemical and mineralogical zonation of the cement paste in contact with the water. It was also noted that the calcium-depleted surface layer was porous and fragile with poor mechanical properties.

Since leaching increases the capillary porosity of cement paste, it can be assumed that the amount of freezable water increases. Powers and Brownyard (1948) stated that nucleation of ice crystals in cement paste becomes easier as the pore size increases. It is therefore reasonable to expect that the frost resistance of concrete subjected to leaching decreases. In accordance with this expectation, the calcium-leached layer of the air-entrained concrete with a w/c-ratio of 0.50 originating from the 55-year old concrete dam was susceptible to frost damage.

Based on the results that leaching makes the concrete surface susceptible to frost action and abrasion, it can be concluded that the leaching kinetics of concrete generally determines the rate of surface deterioration of air-entrained concrete at the waterline. Hence, it would be possible to predict the annual rate of surface deterioration for a particular structure based on careful analysis of the chemical and mineralogical composition of the cement paste just before the winter set in.

Finally, it can be concluded that progressive deterioration of the concrete surface at the waterline of hydro power structures in Sweden begins with leaching during the snowmelt and summer periods. The surface thus becomes susceptible to frost action and abrasion. During the following winter, the outermost surface layer is damaged by frost action and later possibly removed due to abrasion. The process then begins again and surface deterioration continues.

In the case of repairs or new builds, it is a prerequisite that the concrete is properly air-entrained in order to make it frost resistant. Moreover, measures should be taken to increase the ability to resist leaching of calcium compounds. To achieve this, the w/c-ratio can be lowered or part of the cement replaced by supplementary cementitious materials, such as fly ash, slag and silica fume. However, it is of great importance to make sure by careful pretesting that the concrete behaves as expected so that the long-term performance and durability will be satisfactory.

4.6 Summary

The question addressed in this chapter was:

- Which degradation mechanisms are causing progressive deterioration of the concrete surface at the waterline of hydro power structures?

Based on the studies performed, the following conclusions can be drawn:

- Frost action may cause damage to the concrete surface at the waterline of non-air-entrained concrete with a w/c-ratio higher than 0.60.

- Frost action cannot solely account for the surface deterioration of air-entrained concrete with w/c-ratios of 0.50–0.55.

- Leaching of calcium compounds from the concrete surface significantly reduces the ability of the surface to resist frost action and abrasion.

- Long-term exposure to soft river water makes the surface layer of air-entrained concrete highly susceptible to frost damage.

- Interactions between leaching, frost action and abrasion cause surface deterioration of concrete at the waterline of hydro power structures.

5 Internal frost damage at the waterline

This chapter presents experimental studies performed to determine if there is any risk of internal frost damage to concrete at and just above the maximum water level of Swedish hydro power structures (Figure 2-6 e). Both laboratory-cast concrete and concrete from an existing dam were used in the studies. The studies are presented in Paper I and Paper II.

5.1 Frost resistance of concrete at the waterline

As shown in Figure 2-6 (e), internal damage to concrete can be seen just above the maximum water level of some hydro power structures constructed before the 1950s. The damage may be caused by poor frost resistance of the concrete. To determine if there is any risk of internal frost damage to concrete at and above the waterline, concrete specimens were subjected to the frost test described in Paper I.

The same specimens were used as those used in the study to determine whether frost action could account for the surface deterioration at the waterline. After the completion of the frost test, corresponding to 112 freeze-thaw cycles, the splitting tensile strengths of the three concrete mixes with w/c-ratios of 0.54, 0.62 or 0.70 were determined according to Appendix A in EN 12390-6 (SIS, 2009). Prior to the tensile splitting strength tests, the specimens were split into two parts. The upper part had been above the waterline during the test period and the lower part below the waterline. The results were compared with reference specimens kept dry at +20 °C during the frost test period. However, during a period of four weeks prior to the splitting tensile strength tests, all specimens were partially submerged in water at +20 °C in order to obtain similar saturation levels in the concrete.

A slight increase in the splitting tensile strength below the waterline was obtained for all specimens subjected to the frost test compared to the reference specimens. For the air-entrained specimens with a w/c-ratio of 0.54, a slight increase in the splitting tensile strength was also obtained above the waterline. For the non-air-entrained specimens with w/c-ratios of 0.62 and 0.70, the tensile splitting strength above the waterline was reduced by 20–25 % compared to the reference specimens. The latter result indicates the presence of internal cracking due to frost damage. The test procedure and results are further described in Paper II.

As reported in Section 4.2, air-entrained concrete with a w/c-ratio of 0.54 performed well during freeze-thaw tests in the presence of a 3 % NaCl solution, while non-air-entrained concrete with w/c-ratios of 0.62 and 0.70 did not. It can thus be assumed that the poor frost resistance of the latter concrete mixes also means that the risk of internal frost damage increases when non-air-entrained concrete is subjected to climatic conditions similar to those prevailing at the waterline in cold regions. However, frost damage does not occur unless the saturation levels in the concrete exceed the critical degree of saturation (S_{cr}) as stated by Fagerlund (1977). Because S_{cr} is material- and temperature-dependent, the degree of saturation that facilitates frost damage varies with the concrete mix design and the temperature conditions.

5.2 Saturation levels in concrete at the waterline

Every other week during the frost test, one specimen of each concrete mix was cut into 16 pieces and each piece was used to determine the degree of saturation (S). The procedure to determine the saturation levels in a specimen is described in Paper I. The degree of saturation equal to capillary saturation was determined for the three concrete mixes in order to compare the saturation levels in the specimens subjected to the frost test with those values.

In spite of varying results from specimen to specimen, the final saturation levels in the specimens subjected to the frost test correspond rather well to the degree of saturation equal to capillary saturation. Based on the fact that the non-air-entrained specimens with w/c-ratios of 0.62 and 0.70 suffered from internal damage above the waterline, it can be assumed that the saturation levels exceeded the critical degree of saturation (S_{cr}). Given the temperature conditions during the frost test, it can be further assumed that the saturation levels did not exceed S_{cr} for the air-entrained specimens with a w/c-ratio of 0.54. The results of this study are further discussed in Paper II.

For all three concrete mixes, the final saturation levels in the specimens subjected to the frost test far exceeded the saturation levels in reference specimens kept partially submerged in water at +10 °C during the same test period. The results confirm that concrete absorbs more water when subjected to alternating freezing and thawing conditions than at isothermal conditions. Those results are in line with the results obtained by Sandström (2010) and Wikström (2012).

In order to compare the results obtained in this study with saturation levels in an existing structure, concrete cylinders were taken from the upstream face of the 55-

year old dam shown in Figure 2-9 (b) in November 2013. The cylinders were taken 1 m above (-1 m) and at the normal water level (0 m). The saturation profiles are presented in Figure 7-3. The profiles show that the concrete above the waterline is drying, whereas the concrete at the waterline is absorbing water. However, at a distance of 150–200 mm from the surface, the profiles converge at a degree of saturation of approximately 0.8. This value corresponds to the degree of saturation equal to capillary saturation for the concrete originating from the 55-year old dam. The results of this study are further described in Paper II.

5.3 Discussion

This chapter presents experimental studies performed to determine if there is any risk of internal frost damage to concrete at and just above the maximum water level of hydro power structures. Since those structures are in contact with water and simultaneously exposed to freeze-thaw conditions in winter, it can be expected that water transport towards the colder parts of the structures increases due to large temperature gradients. Moreover, high saturation levels in concrete in hydro power structures can be expected, as Sandström (2010) and Wikström (2012) showed that concrete in contact with water and exposed to freeze-thaw conditions absorbs more water than concrete at isothermal conditions.

The results of the studies presented showed that saturation levels in concrete specimens subjected to climatic conditions similar to those prevailing at the waterline of hydro power structures in Sweden were close to capillary saturation. The saturation levels in concrete at and above the waterline of the 55-year old dam (Figure 2-9 b) were also close to capillary saturation. It can thus be concluded that saturation levels in concrete at and above the waterline eventually reach capillary saturation. It can be further concluded that the risk of internal frost damage to concrete at and above the maximum water level is determined by the ability of the capillary saturated concrete to resist freeze-thaw conditions in winter.

Such an assumption is reasonable since the air-entrained specimens with a w/c-ratio of 0.54 did not sustain internal frost damage at or above the waterline while the non-air-entrained specimens with w/c-ratios of 0.62 and 0.70 did. For air-entrained concrete with a w/c-ratio below 0.55, the degree of saturation equal to capillary saturation seems to be too low to induce frost damage due to the protective effects that air entrainment provides. Moreover, it can be concluded that the degree of saturation equal to capillary saturation in non-air-entrained concrete may exceed the critical degree of saturation (S_{cr}) during the winter. Hence, the occurrence of internal damage at and just above the waterline of hydro power structures built of presumably non-air-entrained concrete (Figure 2-6 e) can be explained by insufficient frost resistance of the concrete.

5.4 Summary

The question addressed in this chapter was:

- Is there any risk of internal frost damage to concrete at and above the maximum water level of hydro power structures?

Based on the studies performed, the following conclusions can be drawn:

- Saturation levels in concrete eventually reach capillary saturation at and just above the waterline of hydro power structures in cold regions.

- The risk of internal frost damage is determined by the ability of the capillary saturated concrete to resist freeze-thaw conditions.

- Internal frost damage may occur at and just above the waterline in hydro power structures built of non-air-entrained concrete.

- Hydro power structures built of air-entrained concrete with a w/c-ratio below 0.55 are not likely to suffer from internal frost damage at and just above the waterline due to the protective effect of entrained air.

6 Spalling of concrete in thin dams

This chapter presents experimental studies performed to determine the conditions under which spalling of concrete may occur in thin water retaining concrete structures subjected to long periods of freezing (Figure 2-8). Laboratory-cast concrete were used in the studies presented in Paper VI and Paper VII.

6.1 Development of test method

As shown in Figures 2-9, 2-10 and 2-11, spalling of concrete has been observed far below the normal water level on the upstream face of some thin buttress and arch dams without heat insulating walls on the downstream side. Based on the work of Collins (1944) and field observations by Rogers and Chojnacki (1987), it has been suspected that spalling of hardened concrete may occur due to the growth of macroscopic ice lenses in thin water retaining concrete structures.

During the winter, the water temperature on the upstream side of a dam is slightly above freezing, while the air temperature is below freezing (Eriksson, 1994). In general terms, the dam is subjected to unidirectional freezing, which means in this case that only the downstream face is subjected to freezing temperatures.

During the period when the dam is subjected to unidirectional freezing, a freezing front moves towards the upstream side since heat is conducted towards the downstream side (Figure 6-1). Until balance between heat supply and heat loss at the depth of the freezing front is obtained, it continues to move towards the upstream side. If balance is reached close to the upstream face, where the saturation levels in the concrete are presumably high, the risk of frost damage and/or growth of macroscopic ice lenses are imminent.

To be able to assess the risk of macroscopic ice lens growth in hardened concrete, a new laboratory test method was developed to make it possible to expose one side of concrete specimens to freezing while the other side was in contact with unfrozen water. Concrete mixes with w/c-ratios of 0.85 and 1.0 were used to develop and evaluate this test method. During development, it was shown that macroscopic ice lens growth can occur in low strength concrete. The test setup and the results of the preliminary study are presented in Paper VI.

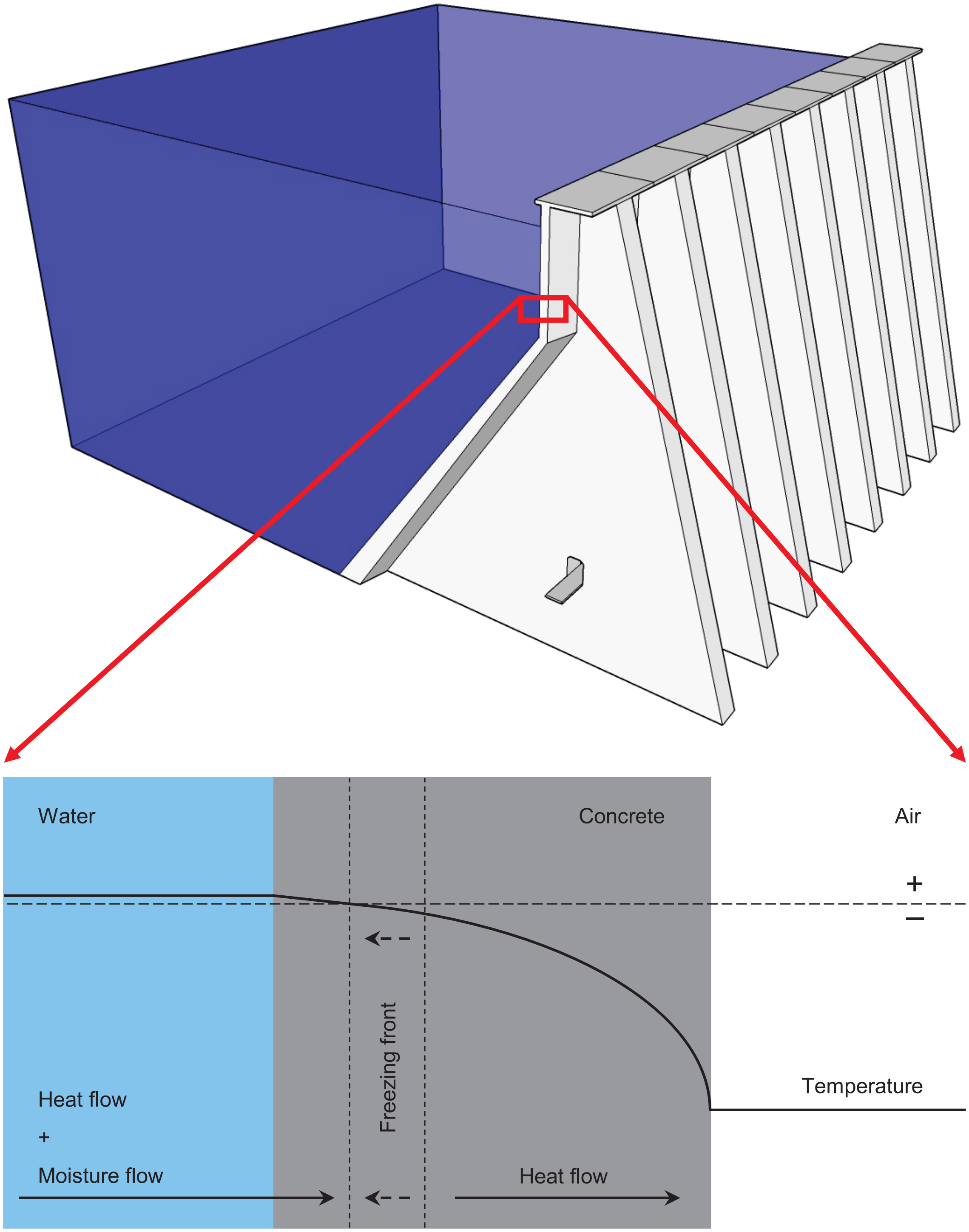

Figure 6-1. Cross-section of a thin concrete buttress dam. During winter, the water temperature is above freezing, whereas the air temperature is below freezing. When heat is conducted towards the cold side, i.e. the downstream side, a freezing front moves towards the upstream side. Under certain conditions, macroscopic ice lens growth may cause concrete spalling of the upstream face.

6.2 Risk of macroscopic ice lens growth

In order to assess the risk of macroscopic ice lens growth in hardened concrete in a systematic manner, eight concrete mixes with w/c-ratios between 0.5 and 1.4 were produced. A Portland cement (CEM I 42.5 N MH/SR/LA) was used as a binder. Moreover, three types of specimens were used in the studies; (1) specimens of mechanically sound concrete, (2) specimens with internal damage due to frost action and (3) specimens with sheets of paper cast into the concrete to represent cavities or other imperfections of the concrete. The production and preparation of the concrete specimens are described in Paper VII.

When the freezing tests were terminated after 235 days for the specimens of sound concrete, the specimens with w/c-ratios of 1.4, 1.2, 1.0 and 0.9 had failed due to macroscopic ice lens growth. It was noted that the lower the w/c-ratio, the longer the period of freezing required before failure occurred. No signs of macroscopic ice lens growth were observed on the specimens with a w/c-ratio of 0.8 or lower. If the specimens had been damaged by frost action prior to the test, macroscopic ice lens growth occurred within a few days regardless of the w/c-ratio.

For the specimens with paper layers cast into the concrete, the freezing tests were terminated after 291 days. By then, specimens of all concrete mixes had failed due to macroscopic ice lens growth. As for the specimens of sound concrete, the lower the w/c-ratio, the longer the period of freezing required before failure occurred. The results of the studies are further discussed in Paper VII.

The growth of ice lenses was uniform over the cross section of the specimens. An ice lens formed in a specimen with sheets of paper cast into the concrete is shown in Figure 6-2 (a–d). The ice lenses could reach a thickness of up to 15 mm before the growth ceased. If the specimens were kept in the freezer long enough, a second ice lens could form below the first ice lens (Figure 6-2 e).

6.3 Discussion

This chapter presents experimental studies performed to determine the conditions under which spalling of concrete may occur in thin water retaining concrete structures. Based on the results of the studies, it is concluded that spalling of concrete due to macroscopic ice lens growth generally should not be an issue in well-compacted low w/c-ratio concrete. However, the effects of ageing, such as leaching and long-term water absorption, will increase the risk of macroscopic ice lens growth in existing structures built of low w/c-ratio concrete.

Saturation levels in concrete may increase due to capillary suction and diffusion of entrained air out of the concrete as suggested by Fagerlund (2006). As the amount of freezable water increases, so does the risk of frost damage. If the critical degree of saturation (S_{cr}) is exceeded and frost damage occurs, macroscopic ice lenses can form regardless of the w/c-ratio since the water permeability increases while the tensile strength decreases. It is demonstrated in Figure 7-3 that saturation levels in concrete far below the normal water level of a 55-year old dam are saturated or close to saturation. Hence, the risk of macroscopic ice lens growth in thin water retaining concrete structures is not only theoretical but also real.

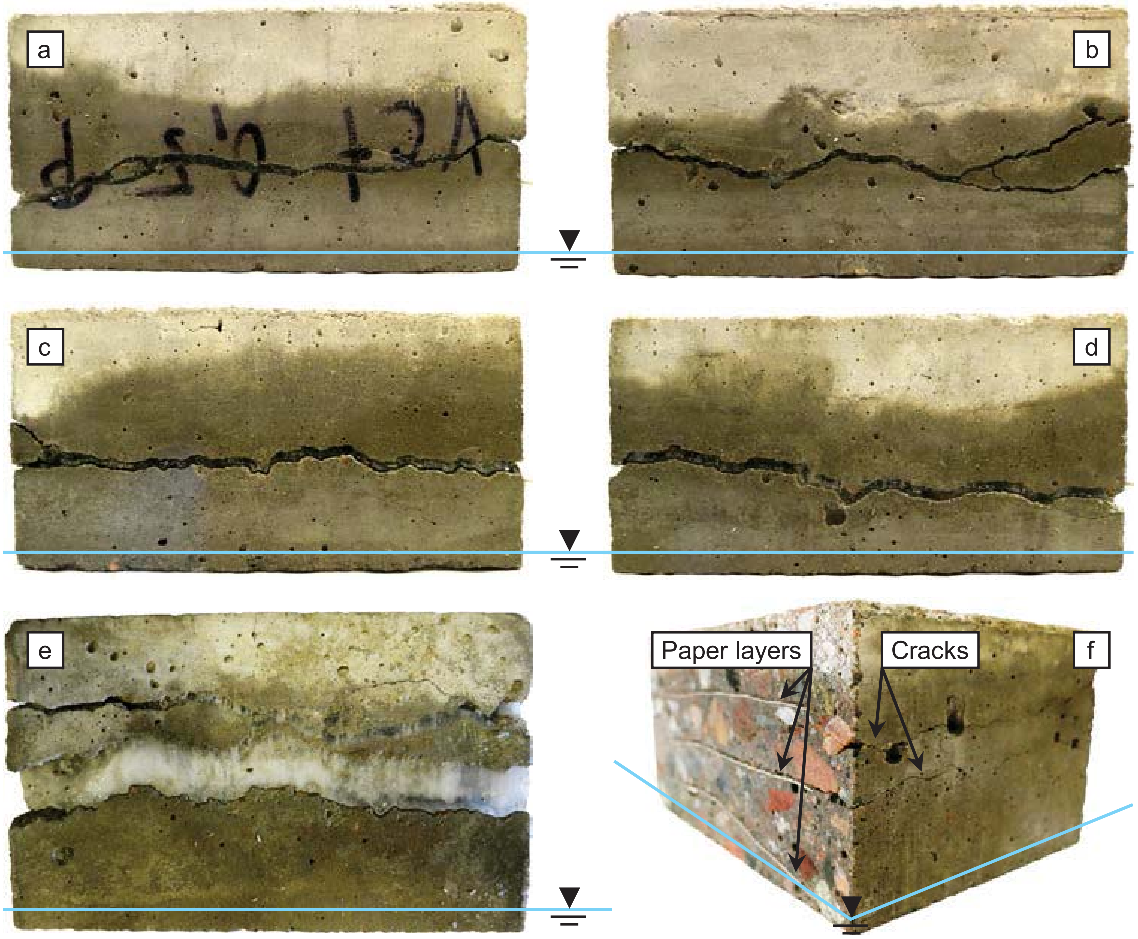

Figure 6-2. An ice lens is visible in a specimen with sheets of paper cast into concrete with a w/c-ratio of 0.5 (a–d). All four sides of the specimen are shown. A second ice lens may eventually form if the test is run for a long-enough time period (e). Paper layers cast into the concrete represent imperfections of the material and may induce cracking of the specimen upon freezing (f).

Furthermore, concrete with cavities or other types of imperfections are also at risk of macroscopic ice lens growth. Sheets of paper were cast into the concrete to create cavities in order to provide space for ice lens growth. The sheets of paper may represent insufficient bond strength between an overlay and the substrate concrete, or various types of imperfections such as voids under the reinforcing steel bars caused by insufficient compaction of the concrete.

Figure 6-2 (f) confirms that macroscopic ice lens growth in the paper layer induces crack growth in the adjacent concrete. A similar process may occur in existing structures exposed to unidirectional freezing. It can thus be concluded that there is a significant risk of macroscopic ice lens growth in thin water retaining concrete structures with cavities and other types of imperfections in the material.

The existence of various types of imperfections in existing structures is difficult to predict. Even with the assumption that imperfections exist, it is difficult to determine their distribution. The examples of concrete spalling at the depth of the reinforcement indicate that imperfections exist and that such imperfections may facilitate growth of macroscopic ice lenses. However, the risk of macroscopic ice lens growth can be minimised by preventing thin water retaining concrete structures from freezing temperatures in winter.

Consequently, many of the large concrete dams in Sweden have been provided with heat insulating walls on the downstream side. In later years, additional dams have been provided with heat insulating walls to reduce the risk of high tensile stresses in the dams caused by seasonal temperature variations. However, many smaller dams are not equipped with heat insulating walls, and are at risk of concrete spalling due to macroscopic ice lens growth since they are exposed to unidirectional freezing in winter.

If not equipped with heat insulating walls, the upstream face of thin concrete dams and other water retaining structures should be inspected on a routine basis since damage far below the normal water level is difficult to observe. Overlooking the risk of macroscopic ice lens growth in concrete may shorten the service life of thin water retaining concrete structures and endanger their structural safety.

6.4 Summary

The question addressed in this chapter was:

- What are the conditions for spalling of concrete in thin water retaining concrete structures subjected to long periods of freezing temperatures?

Based on the studies performed, the following conclusions can be drawn:

- Spalling of concrete may occur due to macroscopic ice lens growth in thin water retaining structures subjected to unidirectional freezing.

- Internal frost damage, cavities and other types of imperfections in the concrete increase the risk of macroscopic ice lens growth.

- The lower the w/c-ratio the longer is the time of freezing required to form macroscopic ice lenses in hardened concrete.

- The risk of macroscopic ice lens growth can be minimised by protecting thin water retaining concrete structures from freezing temperatures.

7 Long-term frost resistance of concrete

This chapter presents experimental studies performed to assess how the frost resistance of air-entrained concrete is affected by long-term submersion in water. Some of the hydro power structures built of air-entrained concrete which suffer from internal frost damage are periodically or permanently under water (Figure 2-7 and 2-8). Both laboratory-cast concrete and concrete from an existing dam were used in the studies. The studies are presented in Paper II and Paper V.

7.1 Water absorption of laboratory-cast concrete

Fagerlund (2006) stated that entrapped air in compaction voids and air voids is dissolved in water when concrete absorbs water in the over-capillary range. When the empty spaces where ice can form gradually fill with water, the frost resistance of concrete can be reduced and eventually completely lost. It is therefore of great interest to be able to predict the rate of water absorption of air-entrained concrete in parts of existing structures which are submerged in water.

To study the water absorption of concrete under water, six micro-concrete mixes were designed with w/c-ratios between 0.45 and 0.70. To lower the proportion of the aggregate, all aggregates larger than 8 mm in size were removed. Hence, the cement content, remaining aggregate content and air content were proportionally increased. The desired air content was 7.5 %. A Portland cement (CEM I 42.5 N MH/SR/LA) was used as a binder. A reference concrete mix with a w/c-ratio of 0.60 and maximum aggregate size of 16 mm was also included in the study. Mix proportions and the fresh and hardened concrete properties are presented in Paper II.

Specimens 95 mm in diameter and 10 mm thick were put in open cages attached to wires hanging from the crest of an arch dam in northern Sweden (Figure 7-1 a–d). The cages were then lowered to depths of 10, 20 and 30 m. To protect the wires from the action of ice in winter, stainless steel profiles were mounted on the upstream face of the dam in 2011; the wires run behind the steel profiles. Since the mounted steel profiles were not damaged by ice action during the winter 2011/2012, the specimens were submerged in June 2012 (Figure 7-2 a–c). Prior to that, the saturation levels were determined for all concrete mixes.

Figure 7-1. Stainless steel profiles (a) to be mounted by divers (b) on the upstream face of the arch dam (d). The top of the steel profiles extend 0.5 m above the maximum water level (c).

Some of the specimens were brought to the surface in October 2014 to once again determine the saturation levels in the concrete (Figure 7-2 d–e). It was noted that the specimens' surfaces appeared rougher and that small sand grains came easily loose during handling. In most of the cases, the measurements showed that the saturation levels were close to, at, or slightly above 1.00. Even in the case of concrete with a w/c-ratio of 0.45 and air content of 7.6 %, the degree of saturation exceeded 0.96. Moreover, the results obtained showed that the saturation levels increased with increasing w/c-ratio and hydrostatic pressure.

The fact that the specimens lost weight during handling and the fact that high temperatures during drying alter the microstructure of the cement paste affected the measurements of the saturation levels. Furthermore, the porosity of the specimens had increased by approximately 20 % in only 28 months, thus indicating that dissolution and diffusion of hydration products had occurred. The results of this study are further described in Paper II.

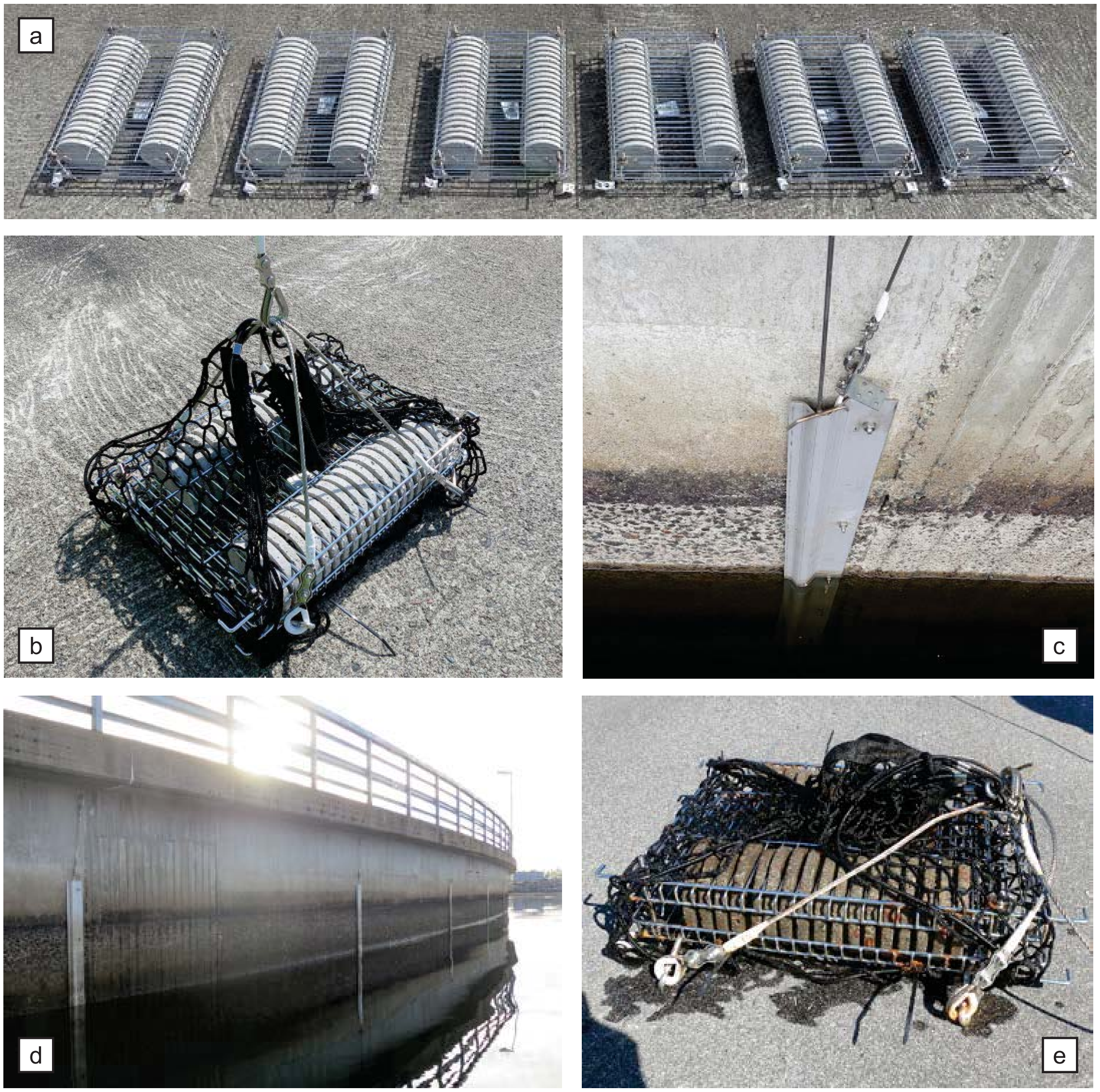

Figure 7-2. Specimens in open cages before submersion at depths of 10, 20 and 30 m in 2012 (a-b). Wires running behind the steel profiles in (c). Status of the steel profiles and specimens in 2014 (d–e).

7.2 Saturation levels in an existing concrete dam

In order to further examine these high saturation levels, concrete cylinders were taken from the upstream face at four different vertical locations on a 55-year old concrete dam (Figure 2-9 b). The four locations were above the normal water level (-1 m), at the normal water level (0 m) and at depths of 10.5 and 18.5 m. Cylinders were also taken from the downstream face at the three lower locations. The cylinders were used to determine the saturation levels across the dam.

The results showed that the air-entrained concrete in the upstream face is more or less saturated at depths of 10.5 and 18.5 m (Figure 7-3). Saturation levels above 1.0 can be explained by the fact that high temperatures during drying alter the microstructure of the cement paste. At the normal water level (0 m), the saturation levels in the outermost 200 mm of the upstream face are above capillary saturation (0.79). Above the normal water level (-1 m), the saturation levels are below capillary saturation. At a distance of 150–200 mm from the upstream face, the two latter profiles converge at a saturation level of approximately 0.80.

Furthermore, the saturation levels gradually decrease towards the downstream face of the dam. The saturation levels in the concrete are approximately 0.70 close to the downstream face at the normal water level and at a depth of 10.5 m. For concrete at a depth of 18.5 m, the saturation levels close to the downstream face are approximately 0.90. Hence, the saturation levels exceed capillary saturation. The saturation profiles are presented and further discussed in Paper II.

As presented in Section 4.4, exposure to the water of the river Ångermanälven causes leaching of the concrete in the upstream face of the dam. As stated by Bertron et al. (2007), leaching of concrete increases the porosity and reduces the mechanical strength of cement paste. In accordance with this statement, the measurements of the concrete porosity showed an increase to over 0.20 in the outermost 15 mm of the upstream face at 18.5 m. For reference specimens, the porosity varied in the range of 0.09 to 0.15. These results are presented in Paper V.

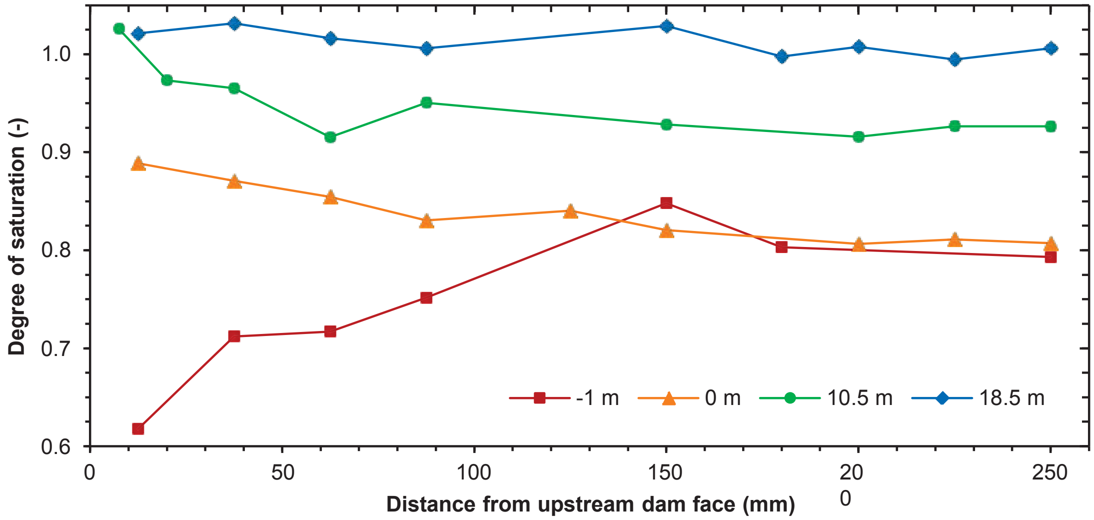

Figure 7-3. Saturation levels in the concrete from the upstream face of the concrete dam shown in Figure 2-9 (b).

As the result of increased porosity, the degree of saturation equal to the capillary saturation increases to over 0.93 compared to reference specimens with values around 0.79. It can thus be assumed that the water content of concrete eventually exceeds the critical degree of saturation (S_{cr}) due to leaching. Hence, the calcium-leached concrete is assumed to become susceptible to frost damage.

Observations made by backscattered electron imaging (BSE) showed that most of the air voids in Zone 2 (see Section 4.4) were filled with secondary ettringite at the normal water level (0 m) and at the depths of 10.5 and 18.5 m. The accumulation of ettringite in Zone 2 can be explained by the increase in SO_3 contents that can be seen in Figure 4-3. Far below the normal water level, many of the air voids in Zone 1 are filled with secondary ettringite and calcium hydroxide crystals (Figure 7-4). However, the air voids in Zone 1 remain empty at the normal water level (0 m). The results of this study are further discussed in Paper V.

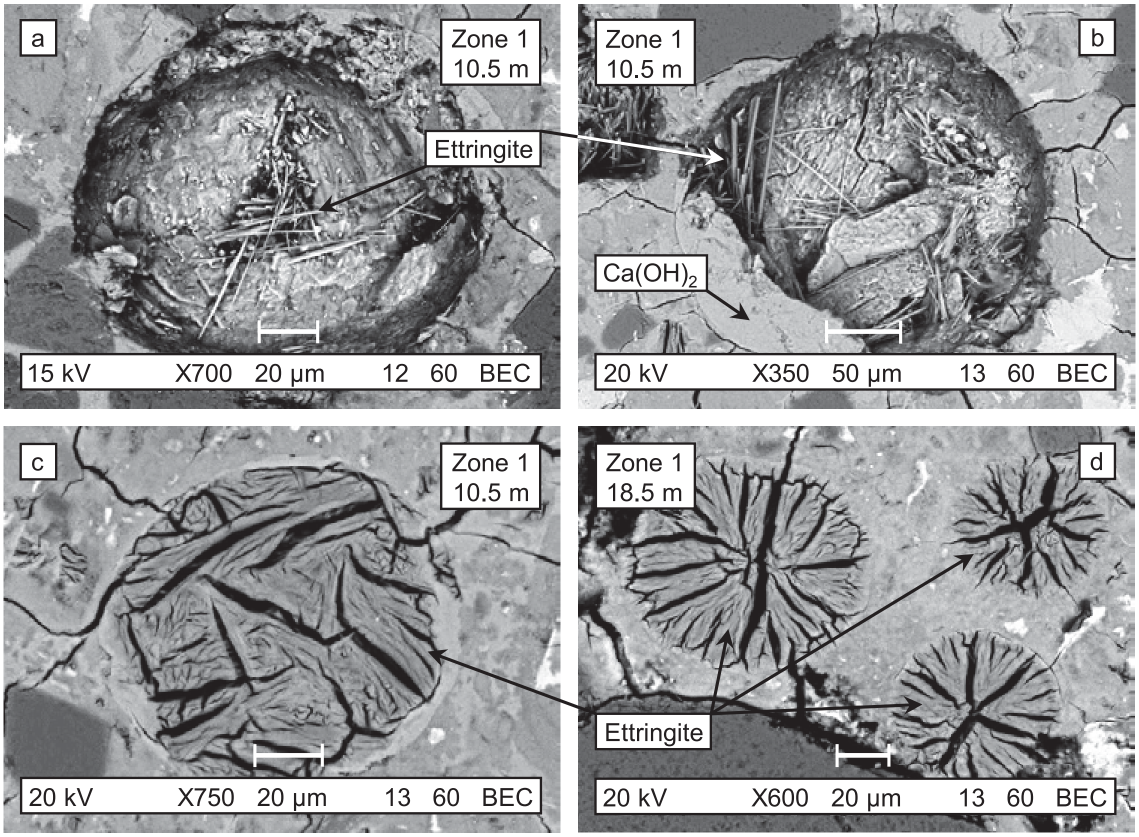

Figure 7-4. BSE images of air voids in Zone 1 (part of the sound zone) at depths of 10.5 and 18.5 m. Some voids are empty while some are filled with calcium hydroxide crystals and massive ettringite formations.

Based on a number of assumptions, it was shown in Paper II that the high levels of saturation obtained in the concrete at the depth of 18.5 m may depend on the fact that the rate of water flow through the flat slab of the dam exceeds the rate of evaporation from the downstream face. Using Eq. (4) and (7) in Section 3.1.5, it was shown that water may accumulate in the concrete over time and gradually fill the air voids. Moreover, the greater the water flow, the more ions from dissolved hydration products are brought into the dam to precipitate as secondary ettringite and calcium hydroxide crystals. This fact could explain why many of the air voids in Zone 1 at the depths of 10.5 and 18.5 m are filled with secondary precipitates while the air voids remain empty in Zone 1 at the normal water level (0 m).

7.3 Discussion

This chapter presents experimental studies performed to assess how the frost resistance of air-entrained concrete is affected by long-term submersion in water. Based on the results of these studies, the air voids in air-entrained concrete gradually fill with water if kept under water for long periods of time. This conclusion is supported by the fact that saturation levels close to 1 were obtained in concrete specimens submerged at depths of 10, 20 and 30 m for 28 months. Moreover, the accuracy of the conclusion is verified by the fact that the saturation levels in concrete far below the normal water level of a 55-year old dam were close to 1. Hence, the water content of air-entrained concrete kept under water will eventually far exceed the degree of saturation equal to capillary saturation.

According to Fagerlund (2006), concrete absorbs water in the over-capillary range due to dissolution of entrapped air in compaction voids and air voids. Fagerlund (1993) reported that the solubility of air in water is proportional to the hydrostatic pressure. It can thus be assumed that saturation levels increase with increasing hydrostatic pressure. The results of the studies presented in this chapter are in line with this assumption. As a consequence of the increasing saturation levels, the risk of frost damage increases. The time until the critical degree of saturation prevails depends on the diffusion rate of air out of the air voids and eventually out of the concrete. It can therefore be concluded that the time until frost damage occurs depends on the concrete mix design, the air content, the hydrostatic pressure and the freeze-thaw conditions a specific concrete structure is subjected to.

In addition to water absorption in the over-capillary range, many of the air voids in concrete fill with secondary precipitates, such as ettringite and calcium hydroxide crystals. The precipitation of those minerals also indicates that the air voids have been partially or fully filled with water. As the air voids gradually fill with water and secondary precipitates, it can be concluded that the ability of the air voids to allow excess water to be pushed into them upon freezing decreases.

Based on the fact that entrained air voids gradually fill with water and secondary precipitates, it can be concluded that the frost resistance of concrete decreases over time. It is thus reasonable to assume that concrete in thin water retaining concrete structures subjected to long periods of freezing eventually will suffer from internal frost damage, which in turn may facilitate the growth of macroscopic ice lenses; see Chapter 6. Moreover, concrete structures in hydro power reservoirs that are subjected to large water level fluctuations are also at the risk of frost damage in the long term. Increasing saturation levels may eventually facilitate internal frost damage in the form of delamination of the vertical concrete surfaces, which are alternately above and below water (Figure 2-7).

In the case of repairs or new builds, it is a prerequisite that the concrete is properly air-entrained in order to make it frost resistant. Measures should also be taken to decrease the diffusivity of air in the concrete. However, it is of great importance to make sure (by careful pretesting) that the concrete mix designs behave as expected so that the long-term performance and durability are satisfactory.

7.4 Summary

The question addressed in this chapter was:

- How is the frost resistance of air-entrained concrete affected by long-term submersion in water?

Based on the studies performed, the following conclusions can be drawn:

- Entrained air voids in concrete will gradually fill with water and secondary precipitates, such as ettringite and calcium hydroxide crystals.
- The rate at which air voids fill with water depends partly on the diffusivity of air in water-filled concrete and partly on the hydrostatic pressure that controls the solubility of air in water.
- Saturation levels in air-entrained concrete can be expected to be close to 1 after long-term submersion in water.
- The frost resistance of air-entrained concrete periodically or permanently kept under water will decrease over time.

8 Conclusions

The basis for this thesis is observations of suspected frost damage to concrete in hydro power structures in Sweden. Based on the experimental studies performed, the following conclusions can be drawn with regard to the long-term performance and durability of concrete in contact with fresh water in cold regions:

- Progressive deterioration of the concrete surface at the waterline of hydro power structures is caused by the combined actions of leaching, frost action and abrasion. The deterioration process begins with leaching during the snowmelt and summer periods since leaching of calcium compounds significantly reduces the resistance of the concrete surface to frost action. During the winter, the calcium-depleted surface layer is damaged by frost action and later possibly removed due to abrasion.

- Saturation levels in concrete at and above the waterline of hydro power structures are equal to those at capillary saturation. For air-entrained concrete with a w/c-ratio below 0.55, saturation levels equal to capillary saturation are below the critical degree of saturation (S_{cr}). The risk of internal frost damage is thus low. For non-air-entrained concrete with a w/c-ratio above 0.60, saturation levels equal to capillary saturation may exceed S_{cr}. The risk of frost damage is thus present. This fact may explain the observations of internal frost damage at and above the waterline.

- Macroscopic ice lens growth can facilitate spalling of concrete in thin water retaining structures subjected to long periods of unidirectional freezing. Cavities and other types of imperfections in the concrete make growth of macroscopic ice lenses possible in low w/c-ratio concrete. The risk of concrete spalling can be minimised by the construction of heat insulating walls in order to protect the structures from freezing temperatures.

- The frost resistance of air-entrained concrete periodically or permanently kept under water can be expected to decrease over time because the saturation levels increase. Entrained air voids gradually fill with water and secondary precipitates, such as ettringite and calcium hydroxide. The rate at which the air voids fill with water depends partly on the diffusivity of air in water-filled concrete and partly on the hydrostatic pressure that controls the solubility of air in water.

9 Future research

The following proposals for future research are partly based on the results of this thesis and partly based on the need to predict the long-term performance and durability of concrete in hydraulic structures in cold regions.

Proposal 1:

Because the leaching of calcium compounds from the concrete surface significantly reduces the resistance of the surface layer against frost action, the relationship between leaching and frost action needs further attention. Knowledge of how the pore structure changes due to leaching would increase the understanding of how the frost resistance of the surface layer decreases. Such knowledge will shed new light on the surface deterioration process of concrete at the waterline of hydraulic structures in fresh water and marine environments. The knowledge can also be used to design new concrete mixes with improved durability.

Proposal 2:

It is well known that emissions of carbon dioxide, CO_2, from the cement industry are substantial. Partial replacement of Portland cement by supplementary cementitious materials (SCMs), such as fly ash, slag and silica fume, will reduce CO_2 emissions. However, concrete mixes with SCMs are also expected to withstand harsh and varying environmental exposure conditions. It is therefore important to develop concrete mix designs suitable for the conditions prevailing in cold regions. The long-term performance and durability of such concretes have to be thoroughly tested, partly based on the findings presented in this thesis.

Proposal 3:

Based on the fact that air voids may fill with water and secondary precipitates, the underlying processes need to be understood in order to be able to predict the long-term frost resistance of concrete periodically or permanently submerged in water. This includes knowledge about the dissolution of air in water and the diffusivity of air in partially and fully saturated concrete. Furthermore, the dissolution of hydration products and the subsequent precipitation of secondary ettringite and calcium hydroxide in the air voids have to be understood. Knowledge about these processes will enhance the understanding of the long-term performance and durability of concrete structures in contact with water in cold regions.

Proposal 4:

The resistance of concrete to single degradation mechanisms is generally assessed by standardised test methods. In reality, many concrete structures are subjected to multiple degradation mechanisms. For example, it was shown in this thesis that the amount of damage caused by the combined effects of leaching, frost action and abrasion exceeds the total amount of damage caused by the mechanisms separately. To evaluate a concrete mix design based on standardised tests may therefore give a misleading indication of its durability. It would therefore be desirable to develop new test methods, which could be used to assess the durability of concrete exposed to relevant boundary conditions and in-situ scenarios.

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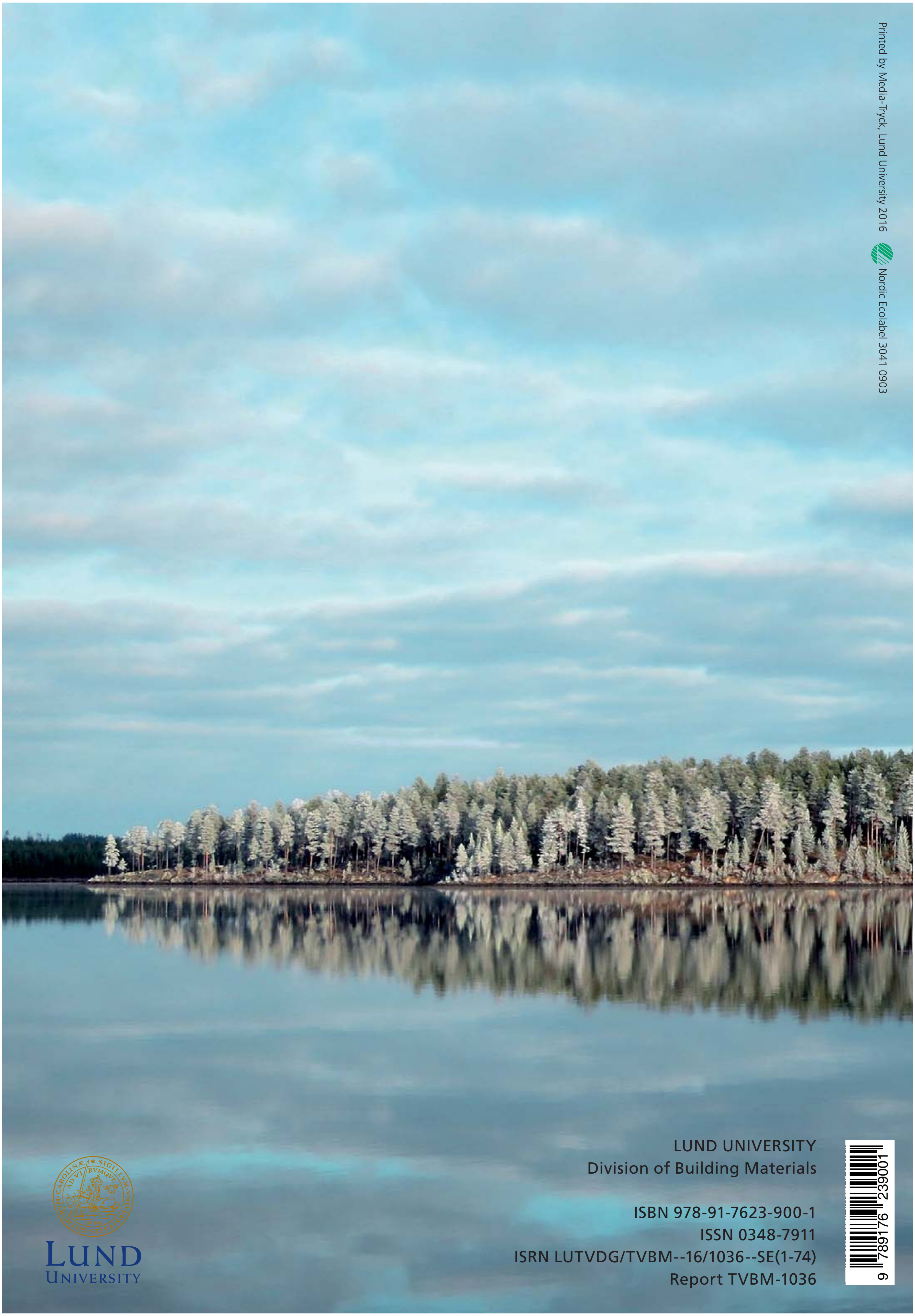

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