Moisture Conditions and Frost Resistance of Concrete in Hydraulic Structures

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Preface

The work presented in this licentiate thesis has been carried out partly at the Division of Building Materials, Lund University, and partly at Vattenfall Research and Development AB, Älvkarleby. The work was started in August 2010 and it has been funded by Elforsk AB (Swedish Electrical Utilities' R&D Company), SBUF (The Development Fund of the Swedish Construction Industry) and SVC (Swedish Hydro Power Centre), to whom I am very grateful.

I would like to thank my supervisors Adjunct Professor Manouchehr Hassanzadeh, Associate Professor Katja Fridh and Professor Lars Wadsö for providing me with their expertise, experience and enthusiasm.

I would also like to thank the laboratory staff at the Division of Building Materials and especially Stefan Backe for his highly appreciated help. Further, I would like to thank the staff at the Älvkarleby laboratory for their support – whenever I needed it. I would also like to thank Christian Stein for spending two months in Älvkarleby helping me out in the laboratory.

Finally, I would like to thank Vattenfall Research and Development AB for giving me the opportunity to undertake part-time postgraduate studies.

Lund, August 2013

Martin Rosenqvist

Summary

Owing to the winter conditions in Sweden, the effects of frost action may have a considerable impact on the deterioration of concrete. Both superficial and internal damage, which are suspected to have been caused by frost action, have been found in concrete in hydraulic structures. These observations have raised questions about the long-term behaviour of hydraulic structures in cold regions.

Superficial damage, similar in appearance to salt scaling of concrete, can be seen at the waterline of hydraulic structures, such as hydro power structures. Progressive damage to the concrete surface results in exposure of coarse aggregate and also exposed reinforcing steel in the long-term perspective.

A possible deterioration process of concrete at the waterline is leaching of the concrete surface, which takes place during the snowmelt runoff period. The concrete surface is thus more susceptible to frost action. During the following winter, the surface layer is damaged by frost action and later removed due to ice abrasion. During the next snowmelt runoff period, the process starts all over again. Experimental results obtained in this work confirm this deterioration process.

Spalling of concrete has been observed below the water level in water retaining concrete structures subjected to long periods of freezing temperatures in winter. The hypothesis is that either poor quality concrete or the effects of aging make hardened concrete susceptible to macroscopic ice lens growth, i.e. ice segregation. Given constant thermal conditions, ice segregation occurs in undamaged concrete with water to cement-ratio (w/c-ratio) 0.9 or higher. In frost-damaged concrete, ice segregation occurs within a few days regardless of the w/c-ratio. Ice segregation may also occur in concrete with cavities or imperfections. The period of freezing required to facilitate ice segregation increases with decreasing w/c-ratio. Hence, the risk of concrete spalling in actual structures cannot be overlooked since unfavourable temperature and moisture conditions may exist in winter.

Knowledge about concrete deterioration is important in order to improve the efficiency of maintenance of hydraulic structures. However, the overall purpose of gathering knowledge about damage mechanisms is to secure and to be able to safely extend the service life of hydraulic structures.

Keywords: Hydraulic Structures, Hydro Power, Concrete Dams, Concrete, Frost Resistance, Scaling, Spalling, Moisture Absorption, Macroscopic Ice Lens Growth

Sammanfattning

Med avseende på de svenska förhållandena vintertid kan frostpåverkan antas ha betydande inverkan på nedbrytningen av betong i vattenbyggnader. Både ytliga och inre skador, vilka misstänks ha orsakats av frostpåverkan, har upptäckts på betong i exempelvis vattenkraftkonstruktioner. Nämnda observationer har väckt frågor om vattenbyggnaders beständighet i ett kallt klimat.

Ytligt belägna skador, vilka utseendemässigt påminner om avskalningar orsakade av tösaltning, kan i många fall ses längs vattenlinjen på vattenbyggnader. En successiv avskalning av betongytan leder till friläggandet av grövre ballastkorn, samt i ett längre perspektiv även till friläggandet av armeringsjärn.

Ett möjligt scenario för nedbrytningen av betongytan längs vattenlinjen är att den utsätts för urlakning under snösmältningsperioden. Betongytan blir därmed känslig för frostpåverkan och skadas således under den följande vintern. På våren nöts det skadade skiktet bort av is och under nästa snösmältningsperiod börjar processen om på nytt. Erhållna resultat från försök i detta arbete styrker nämnda scenario för betongytans nedbrytning.

Ett flertal exempel på spjälkning av betong har påträffats under vattennivån i dämmande betongkonstruktioner. Dessa konstruktioner har vintertid varit utsatta för långa perioder av frostpåverkan. En hypotes är att dålig betongkvalitet eller effekterna av åldring möjliggjort makroskopisk islinsbildning i betong. Erhållna resultat visar att vid stationära temperaturförhållanden kan spjälkning inträffa i oskadad betong med vattencementtal (vct) 0.9 eller högre. I frostskadad betong inträffar däremot spjälkning redan inom några få dagar oavsett betongens vct. I betong med håligheter eller andra svagheter kan också spjälkning inträffa. Dock krävs det allt längre perioder med frostpåverkan i takt med ett lägre vct. Risken för spjälkning av betong i verkliga konstruktioner kan således inte förbises, eftersom ofördelaktiga temperatur- och fuktförhållanden kan existera vintertid.

Kunskap om betongens nedbrytning är viktig i syfte att förbättra och effektivisera underhållet av betong i vattenbyggnader. Det övergripande syftet med kunskap om skademekanismer är dock att kunna säkerställa och möjliggöra säker förlängning av livslängden för vattenbyggnader.

Nyckelord: Vattenbyggnader Vattenkraft, Betongdammar, Frostbeständighet, Betong, Avskalning, Spjälkning, Fuktupptagning, Makroskopisk Islinsbildning

Symbols and Abbreviations

d	Cross-sectional dimension	m
D_l	Moisture transport coefficient	kg/(m·s·Pa)
F	Maximum load	N
f_{ct}	Splitting tensile strength	Pa
J_l	Liquid flow	$kg/(m^2 \cdot s)$
J_s	Saturated flow	$kg/(m^2 \cdot s)$
J_v	Vapour flow	$kg/(m^2 \cdot s)$
k_p	Permeability coefficient	kg/m
L	Length	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)	-

υ	Water vapour content	kg/m^3
υ_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	°
π	3.14	-
σ	Surface tension	Pa
φ	Relative humidity	-
∂	Change/difference	-
AAR	Alkali-aggregate reaction	-
ACR	Alkali-carbonate reaction	-
ASR	Alkali-silica reaction	-
C_3A	Calcium aluminium hydrates	-
C_4AF	Calcium aluminium iron hydrates	-
CH	Calcium hydroxide – $Ca(OH)_2$	-
CSH	Calcium silicate hydrates	-
ITZ	Interfacial transition zone	-
RH	Relative humidity (φ)	-
w/c	Water to cement (ratio)	-

List of Publications

Appended Papers (manuscripts)

PAPER I — Rosenqvist, M., Oxfall, M., Fridh, K., Hassanzadeh, M., 'A Test Method to Assess the Frost Resistance of Concrete at the Waterline of Hydraulic Structures', (submitted)

PAPER II — Rosenqvist, M., Fridh, K., Hassanzadeh, M., 'Macroscopic Ice Lens Growth in Hardened Concrete', (submitted)

Other Publications by Author

i — Rosenqvist, M., 'Moisture Transport in Concrete Structures in Swedish Hydro Power Plants', Proceedings of XXI Nordic Concrete Research Symposium, Hämeenlinna, Finland, 2011, p.159-162

ii — Rosenqvist, M., Persson, M., Hassanzadeh, M., Fridh, K., 'Frost Damage in Concrete in the Waterline of Porsi Hydro Power Plant', Proceedings of International Symposium on Modern Technologies and Long-term Behavior of Dams, Zhengzhou, China, 2011, p.447-454

iii — Rosenqvist, M., Fridh, K., Hassanzadeh, M., '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, 2012, p.658-664

iv — Rosenqvist, M., Nordström, E., Hassanzadeh, M., Fridh, K., 'Observations and Investigations of Frost Damage Mechanisms of Concrete Dams in Sweden', Proceedings of the 81st Annual Meeting Symposium of ICOLD, Seattle, USA, 2013, p.403-413

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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. Dams, harbours and canals are all examples of hydraulic structures. Bridge foundations in water only affect the water flow to some extent. Nevertheless, bridge foundations are also referred to as hydraulic structures in this thesis.

Concrete structures submerged, or partially submerged, in water and occasionally subjected to frost action are at risk of frost damage in winter. Frost action is defined as the combined effects of freezing and subsequent thawing of varying duration. Concrete in hydro power structures, harbours, canals and bridge foundations are all exposed to the risk of frost damage in cold regions. Since concrete with high moisture content is susceptible to frost action, the frost resistance is a very important characteristic of concrete in hydraulic structures.

The design life of hydraulic structures of concrete has traditionally ranged from 50 to 100 years. The expected useful lifetime of these structures, termed service life, has normally been the same as the design life. In some cases, it might have become economically attractive to extend the service life of hydraulic structures as time has passed by. One of the consequences of extending the service life without taking measures is that it then may exceed the original design life. Hence, the extension of service life of hydraulic structures of concrete is closely related to the issue of durability of concrete.

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

Deterioration of concrete can be caused by a great number of events. Durability problems of concrete in hydraulic structures are often associated with high moisture content, such as the risk of frost damage. Concrete structures submerged, or partially submerged, in water may also be deteriorated by exposure to pure water or aggressive agents, such as chlorides and sulphates. Destructive cracking of concrete structures can be caused by, for example, extreme loads, seasonal temperature variations and chemical reactions between cement and aggregate causing swelling.

Detailed knowledge of damage mechanisms and properties of concrete is crucial in order to understand deterioration of concrete. This knowledge can be used to design concrete mixes with adequate resistance to deterioration. In Sweden, deterioration of concrete structures submerged, or partially submerged, in any body of fresh water is mostly caused by leaching, frost action and erosion.

1.2 Presentation of the Study

Owing to the winter conditions in Sweden, the effects of frost action may have a considerable impact on the deterioration of concrete structures. Both superficial and internal damage, which are suspected to have been caused by frost action, have been found in concrete in hydro power structures. These observations have raised questions about the long-term behaviour of concrete in hydraulic structures in cold regions.

Based on observations of concrete damage and the fact that the service life has exceeded, or will exceed, the original design life of many hydraulic structures, the following questions have been identified with respect to frost action:

- Which deterioration processes cause progressive damage to the concrete surface at the waterline of hydraulic structures?
- What are the conditions for concrete spalling in 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 at different depths?

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

There are approximately 1 800 hydro power plants and more than 30 000 bridges in Sweden. Concrete structures submerged, or partially submerged, in water can be found in the majority of hydro power plants. In the case of bridges, not all of them are built of concrete and not all of them have foundations in water. Yet, the total value of all hydraulic structures of concrete in hydro power structures, harbours, canals and bridges is tens of billions of Euros.

Detailed knowledge about deterioration processes and damage mechanisms is important in order to improve the efficiency of maintenance of concrete structures. However, the overall purpose of gathering detailed knowledge about deterioration processes and damage mechanisms is to secure and to be able to safely extend the service life of hydraulic structures subjected to frost action.

1.3 Scope and Limitations

The present study is divided into four parts:

- Part 1 – Frost Resistance of Concrete at the Waterline
- Part 2 – Interaction between Leaching, Frost Action and Abrasion
- Part 3 – Macroscopic Ice Lens Growth in Hardened Concrete
- Part 4 – Moisture Absorption of Concrete Submerged in Water

The first part of this study is based on field observations of progressive damage to the concrete surface at the waterline of hydraulic structures in Sweden. The frost resistance of concrete at the waterline was studied in the laboratory.

Even though the resistance of concrete to a certain deterioration process is good, the effects of additional deterioration processes may significantly reduce the resistance to the first deterioration process. Since hydraulic structures are often subjected to several deterioration processes, synergy may occur. The effects of interaction between leaching, frost action and abrasion on the deterioration of the concrete surface were studied in the laboratory.

Field observations of concrete spalling on the upstream and downstream face of some thin concrete dams form the basis for the third part of this study. The risk of macroscopic ice lens growth in hardened concrete in structures subjected to long periods of freezing temperatures was studied in the laboratory. Macroscopic ice lens growth is termed frost heave when it occurs in soils in winter.

Moisture absorption of air entrained concrete submerged in water at different depths is studied in the fourth part of this study. There are concerns about the long-term performance of air entrained concrete submerged in water. If entrained air is gradually replaced by water or hydration products, the frost resistance can be reduced. Measurements of the degree of saturation of concrete submerged in water are performed both in the laboratory and in the field.

Only effects of the Swedish climatic conditions on the deterioration of concrete in hydraulic structures are studied. However, the results may also be useful to help understand deterioration of concrete in hydraulic structures in other countries with cold climates. Further, the experimental work is focused on concrete structures in fresh water bodies. The effects of de-icing chemicals on the scaling resistance of concrete are not considered in this study.

Concrete of poor quality was used for the construction of hydraulic structures in Sweden in the early 20th century. Many of those concrete structures were severely damaged and extensive repairs were carried out only some decades after the commissioning. Since repaired concrete in those structures differs from the original concrete, there is no need to study these original types of concrete. Only types of concrete used since the 1930s are considered in this study.

The basis for the present study is observations of concrete damage in hydro power structures in Sweden. The experimental tests are focused on the effects of frost action on the deterioration of concrete in hydro power structures. However, the experimental tests and the results obtained are in many cases also applicable to concrete structures in harbours, canals and bridge foundations.

1.4 Outline of the Thesis

Chapter 2 gives a brief background on the hydro power development in Sweden, common types of concrete dams and exposure conditions for hydraulic structures.

Observations of damage to concrete in hydro power structures are presented in Chapter 3 as well as a summary of advances in concrete technology during the hydro power development in Sweden. A brief summary of damage mechanisms of concrete in hydraulic structures and some physical properties of concrete related to moisture fixation and moisture transport are also presented in Chapter 3.

The results obtained in the study on deterioration of concrete at the waterline of hydraulic structures are presented in Chapter 4. Further, the results obtained in the study on the effects of interaction between leaching, frost action and abrasion on the deterioration of the concrete surface are presented in Chapter 5.

The study of conditions for macroscopic ice lens growth in thin water retaining concrete structures subjected to long periods of freezing temperatures is presented in Chapter 6. The work conducted so far in the study of moisture absorption of concrete submerged in water at different depths is presented in Chapter 7.

Chapter 8 gives a discussion on the durability of concrete in hydraulic structures based on the results obtained in the experimental studies. The most important conclusions drawn are finally presented in Chapter 9.

Four proposals for future research are presented in Chapter 10.

2 Hydro Power in Sweden

2.1 Development of Hydro Power

The development of hydro power for electricity production was initiated in the late 19th century and made the large scale industrialization in Sweden possible. The increasing demand for electricity led to a boom in the number of power plants commissioned during the first decades of the 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 shortages in Sweden. Hence, the majority of the hydro power plants were commissioned between 1945 and 1975.

According to Swedish Energy (2013), about 1 800 hydro power plants are currently in operation in Sweden. The total installed capacity is 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. That corresponds to approximately 45% of the electricity used in Sweden in a year.

In times of concern about the impact of global climate change due to emissions of greenhouse gases, the emissions of carbon dioxide, CO2, 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 utilization 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. The rotating generator converts the mechanical energy into electricity. The used water continues through the draft tube (and tailrace) before re-entering the river.

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

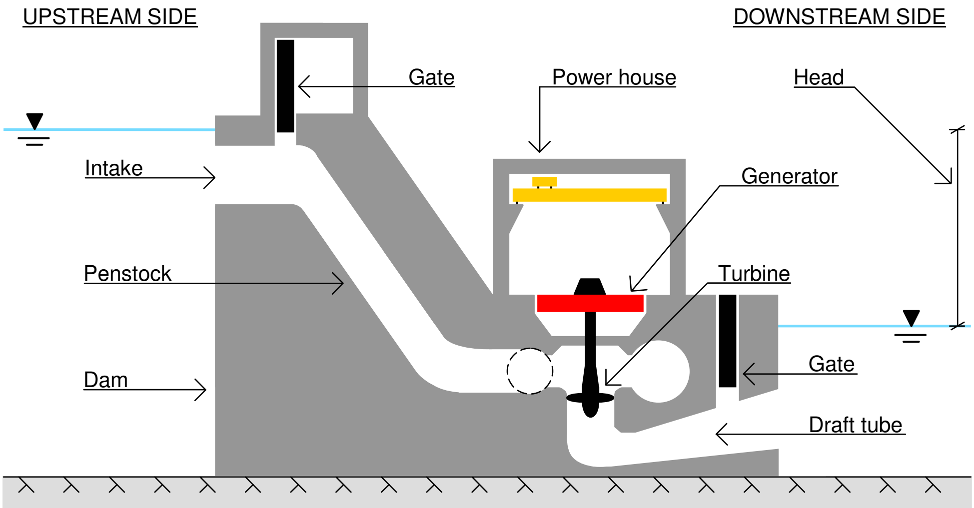

Figure 2-1. Cross section of a hydro power plant.

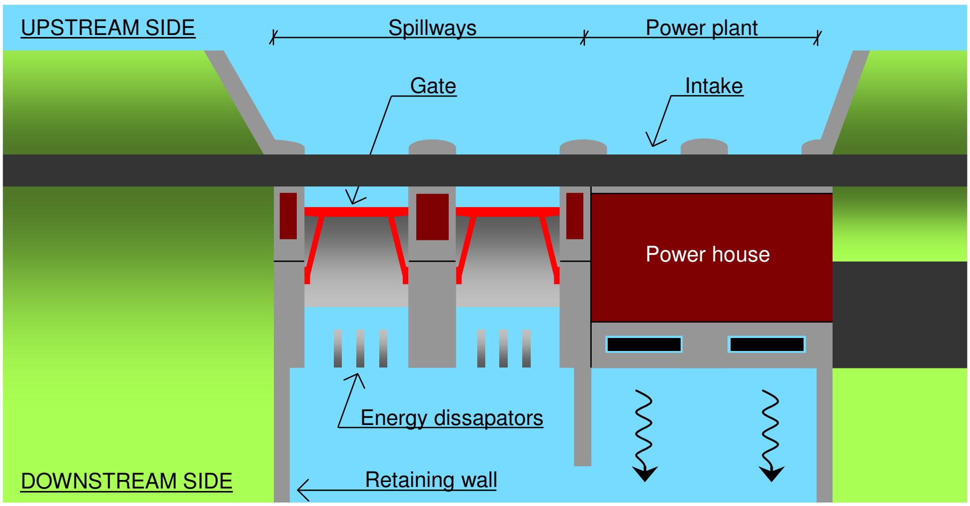

Figure 2-2. Plan of a hydro power plant. Electricity is generated in the power house, whereas surplus water can be released in the spillway.

2.2 Types of Concrete Dams

As the demand for electricity increased in the late 19th century, more generating capacity was needed. Plans for the construction of larger dams were developed. Up to then, the construction of stone masonry dams was most common. However, the construction of stone masonry dams was time consuming and thus expensive. The introduction of concrete and reinforced concrete as building materials made the construction of larger dams possible at reasonable costs.

Concrete dams can roughly be classified into gravity and arch dams. Gravity dams are designed to use only the force of gravity to resist the hydrostatic pressure, whereas arch dams transfer the force of the retained water laterally into the abutments. Both gravity and arch dams can be classified into additional categories. In the following sections, some Swedish types of concrete dams are presented.

2.2.1 Solid Gravity Dam

The solid gravity dam uses its own dead weight to resist the hydrostatic pressure trying to overturn the dam (Figure 2-3). The upstream face of the dam is either vertical or somewhat inclined towards the downstream side. An inspection gallery running through the dam can normally be found in the lower part of the dam. The dam is divided into vertical sections by dilatation joints.

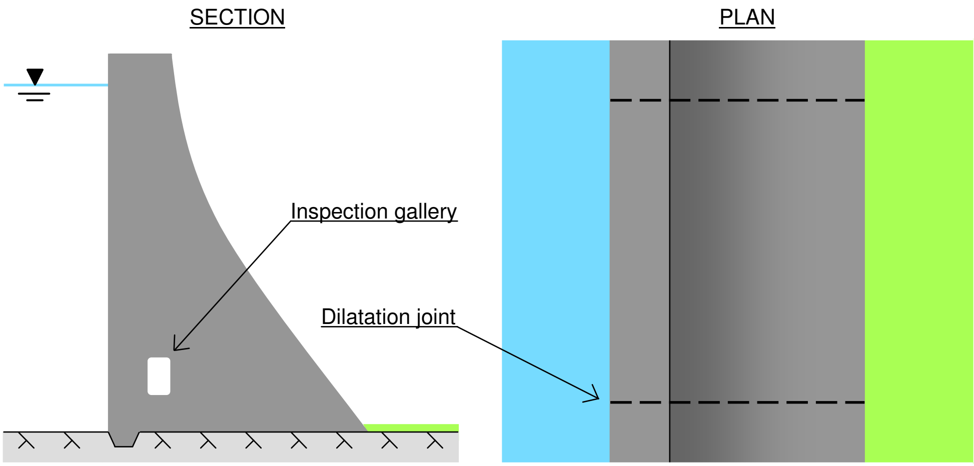

Figure 2-3. Section and plan of a solid gravity dam.

Cut stones were used for the construction of gravity dams until about 1900 when the use of unreinforced concrete became common. Cement-rich concrete was used in the upstream face to improve the water tightness, whereas lean concrete was used in the rest of the dam. A drainage system, consisting of vertical drainage pipes, was installed between the inspection gallery and the upstream face. The drainage system was meant to collect and lead water away in the event of leakage.

However, the drainage system was not able to protect the lean concrete from total destruction due to percolating water. Already after some 10 to 20 years in service, the need for extensive repairs was evident. The construction of solid gravity dams, according to the design shown in Figure 2-3, came to an end about 1930.

2.2.2 Solid Gravity Dam with Flat Slab

Westerberg (1951) reported that the solid gravity dam design was completed with a flat slab on the upstream side of the dam in the early 1930s (Figure 2-4). The main body of the dam could either be made from lean concrete or stone masonry. The dam is divided into vertical sections by dilatation joints.

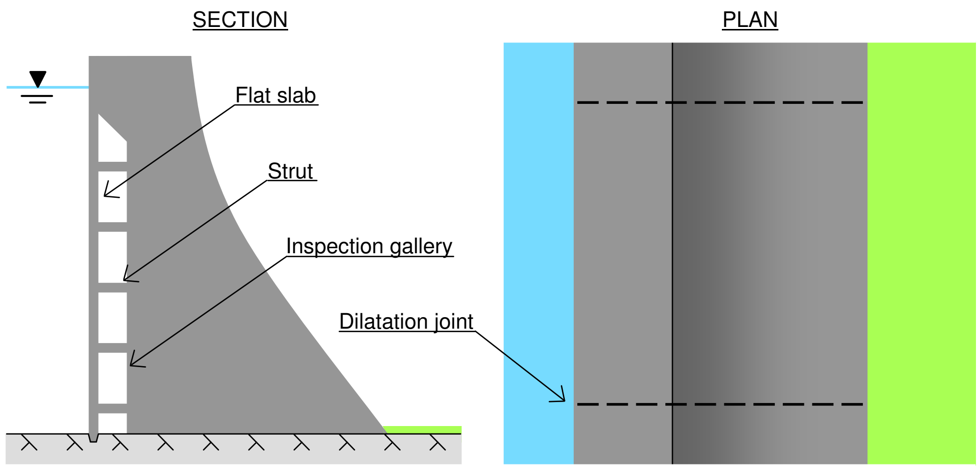

Figure 2-4. Section and plan of a solid gravity dam with flat slab.

The flat slab was meant to be water tight and thus protect the lean concrete in the main body of the dam. The flat slab and struts were heavily reinforced. Concrete with high cement content and low water to cement ratio (w/c-ratio) was used. In the event of leakage, the damage could be repaired from the space between the flat slab and the main body of the dam, which was used as an inspection gallery.

However, the construction of the solid gravity dam with flat slab was expensive. In addition to the main body of the dam, the construction of the flat slab and the struts required complicated and time consuming formwork. This type of gravity dam was only built during the 1930s and 1940s.

2.2.3 Buttress Dam

The buttress dam consists of a flat slab supported by walls (Figure 2-5). The flat slab is heavily reinforced and the walls, also called buttresses, are spaced at intervals on the downstream side. Buttress dams are also called hollow gravity dams. Most of the buttress dams can be classified into the heavy or thin types.

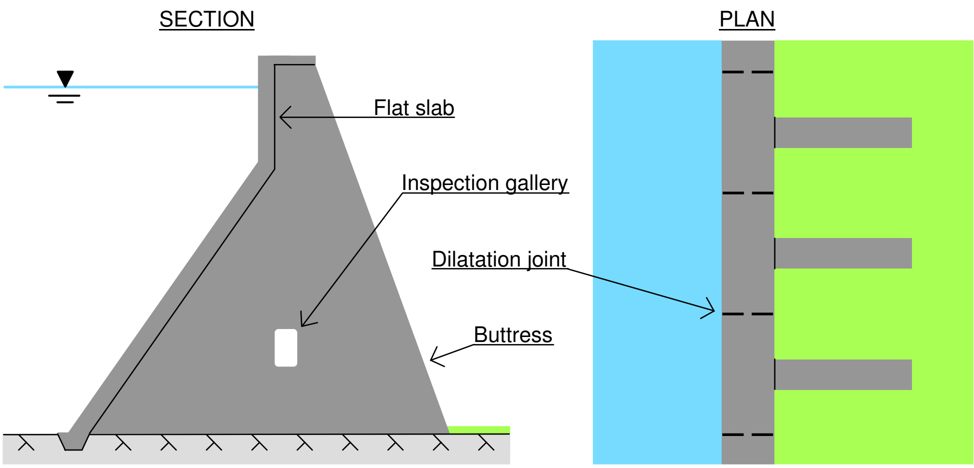

Figure 2-5. Section and plan of a buttress dam (hollow gravity dam).

A buttress dam of the heavy type uses only the dead weight of the dam to resist the hydrostatic pressure. The flat slab is normally vertical or somewhat inclined towards the downstream side. A buttress dam of the thin type also takes advantage of the hydrostatic pressure to hold it down. The flat slab is vertical on the upper part of the dam, while it is inclined further down. A section of a buttress dam of the thin type is shown in Figure 2-5.

According to Edlund (1961), the first Swedish buttress dam of the heavy type was built in the 1930s. Due to the buttress dam design, the risk of thermal cracking was reduced since less concrete was needed. The clear spaces between the buttresses increased the cooling rate of concrete. The amount of concrete needed was further reduced for buttress dams of the thin type. Both buttress dams of the heavy and thin types are divided into vertical sections by dilatation joints.

2.2.4 Arch Dam

Arch dams are normally thin and require much less concrete than any other type of dam. The arch dam curves upstream while the force from the water behind it pushes the dam into its foundations (Figure 2-6). Therefore, the rock at the dam site has to be strong enough to carry the forces imposed by the dam. Arch dams are normally suitable for narrow and steep sided valleys. Since most valleys are broad in Sweden, arch dams are rather rare. Consequently, other types of dams are more suitable. Arch dams are normally provided with vertical contraction joints.

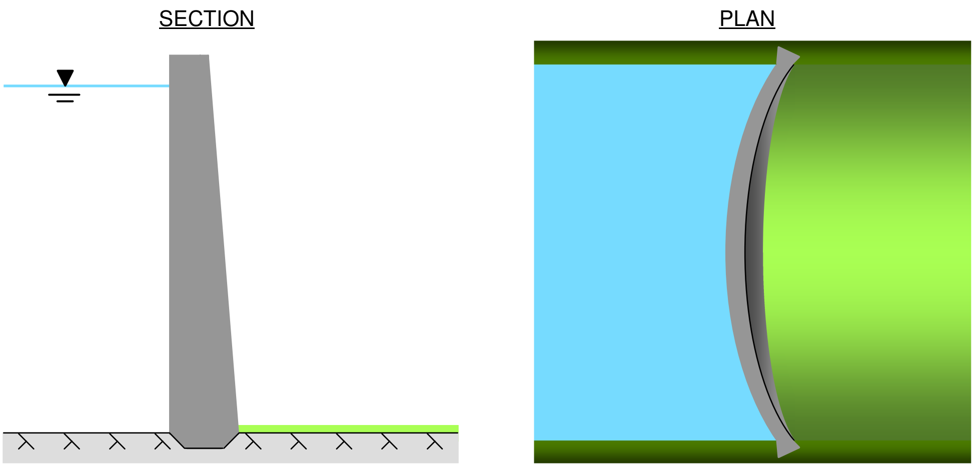

Figure 2-6. Section and plan of an arch dam.

2.2.5 Multiple-Arch Dam

A multiple-arch dam consists of several contiguous arches facing upstream. The arches are supported by buttresses placed at intervals on the downstream side (Figure 2-7). Multiple-arch dams have usually been constructed at remote areas since less concrete has been needed in comparison with other dam types. Sällström (1967) reported that temperature induced stresses often resulted in cracking of the arches due to large variations between summer and winter temperatures. Consequently, the multiple-arch dam did not become very popular in Sweden.

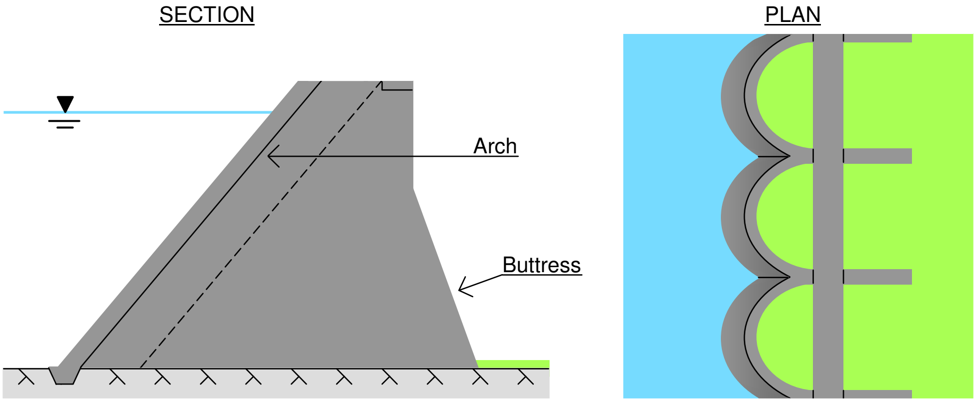

Figure 2-7. Section and plan of a multiple-arch dam.

2.2.6 Other Types of Dams

In addition to the dams presented above, more types of concrete dams exist worldwide. The Hoover Dam is a typical example of an arch-gravity dam, which is a combination of the arch and gravity dam designs. There also exist additional types of arch and buttress dams. In the latter case, the Ambursen dam has to be mentioned. The Ambursen dam is the original buttress dam having a heavily reinforced and inclined flat slab on the upstream side. The Ambursen dam was built in large quantities in the United States and Norway (where the engineer Nils F. Ambursen was born), during the first half of the 20th century.

2.2.7 Spillways

Spillways are used to safely release surplus water from the reservoir behind the dam (Figure 2-2). Most spillways in concrete dams are of the solid gravity dam type or the buttress dam type. Spillways are normally provided with steel gates, which can be opened to release water. Most spillways are adjacent to the power house and/or the main dam.

2.2.8 Retaining Walls

River banks close to hydro power intakes and/or spillways are normally protected with retaining walls (Figure 2-2). In addition to hydro power structures, retaining walls are also used in harbours and canals. There are different types of concrete retaining walls, such as gravity walls, cantilever walls and anchored walls.

The gravity wall uses its own dead weight to resist the force from the backfill. The cantilever wall is often in the shape of an inverted T. The dead weight of the landfill counteracts the forces trying to overturn the wall. The anchored wall uses cables or stays anchored in the rock or soil behind it to resist the force from the backfill.

2.3 Exposure Conditions

The climate in Sweden is variable. Summers are warm and winters are cold. In the southern part 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. Even larger temperature differences may occur occasionally. Air temperatures down to -30 °C are common during winter in the northern parts of the country.

The temperature of concrete in hydraulic structures, and especially of the surface, 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. The temperature of a concrete surface may increase due to radiation from the sun. On the contrary, the losses of heat by radiation at night may lead to the fact that the surface temperatures become lower than the air temperature.

In both 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.

Due to sub-freezing temperatures in the air, the surface of water bodies is normally covered with ice in winter. Formation of ice covers can be prevented by turbulent water flow. Consequently, open water surfaces can be seen at intakes, spillways and on the downstream side of power houses. In spite of turbulent water flow, a band of ice frozen solid to the concrete surface can be seen at the waterline of hydraulic structures (Figure 2-8 A). The band of ice is formed in spite of a water temperature above the freezing point. The thickness of the band of ice decreases with increasing depth from the waterline.

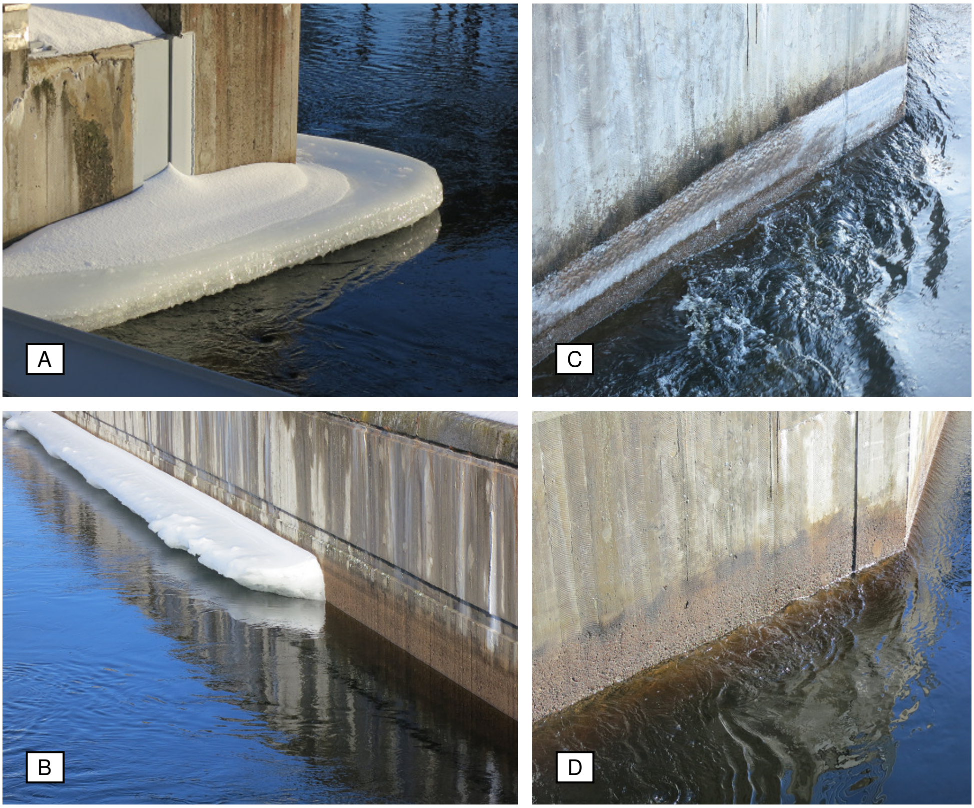

Figure 2-8. In winter, a band of ice frozen solid to the concrete surface can be seen at the waterline of hydraulic structures (A). In spring, the band of ice falls off when the air temperature rises (B). In both spring and autumn, the air temperature frequently crosses the freezing point of water. A 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).

The band of ice falls off when the air temperature starts to rise in spring (Figure 2-8 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 2-8 C-D).

The ice cover 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 a hydraulic structure, the ice floes push against the structure until they break apart into pieces or melt away (Figure 2-9).

Figure 2-9. Ice floe pushing against a bridge column in spring.

Due to the geology of Sweden, the ion concentration of the water in Swedish rivers is low in comparison with most other rivers around the world. 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. The concentration of calcium (Ca^{2+}) in the river water can be used as an example. Measurements in June and July showed a lowered concentration of calcium in the river water in comparison with measurements in August and September. Also the pH value of the river water was somewhat lower in June and July in comparison with the value in August and September. The lower concentration of alkali ions in the river water during the snowmelt runoff period may explain the lower pH values in June and July.

Drugge (2001) showed that the pH value of the water in the river Lule älv varied between 6.9 and 7.8. The differences in the pH value depended on the location and point of time for the measurements. 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.

3 Structures and Materials

3.1 Damage to the Concrete Surface at the Waterline

Progressive damage to the concrete surface can be observed at the waterline of hydraulic structures, such as dams, harbours, canals and bridge foundations. Progressive disintegration of the cement paste leads to exposure of coarse aggregate (Figure 3-1 A-C). The greatest amount of damage can be seen at the waterline, which normally corresponds to the maximum water level. The amount of damage decreases with increasing water depth. At structures where the water level regularly varies, damage is distributed between the minimum and maximum water level (Figure 3-1 B). At hydraulic structures where the water level is relatively stable, damage is concentrated to the waterline (Figure 3-1 C).

This type of concrete damage to hydraulic structures is sometimes assumed to be caused by drifting ice floes. Abrasive wear of concrete can occur if ice floes push against the structures. This is probably true regarding hydro power intakes and spillways on the upstream side. The river current leads ice floes to the structures. However, progressive damage to the concrete surface can be seen both on the upstream and downstream side of dams (Figure 3-1 B).

Except in the vicinity of intakes and spillways, the water is more or less stagnant on the upstream side of a dam. The water body is normally covered by ice in winter. According to ICOLD (1996), the ice cover breaks approximately parallel to the banks, shores and structures if the water level fluctuates. Still, a band of ice remains frozen solid to stones, masonry and concrete at the former waterline. The band of ice may protect the concrete surface from abrasive wear by drifting ice floes until it is melted away.

On the downstream side of a dam, the water flows away from the dam and carries away ice floes. Hence, no ice floes can push against the structures. Formation of ice covers on the downstream side of hydro power plants is normally prevented by turbulent water flow. Nevertheless, progressive damage to the concrete surface at the waterline can be seen on the downstream side of hydraulic structures.

Figure 3-1. Photos of damage to the concrete surface at the waterline of hydro power structures. The photos A and C are taken on the upstream side, whereas the photo B is taken on the downstream side of the dams.

Deterioration rates of up to 1 mm per year have been observed at the waterline of hydro power structures. Such deterioration rates may expose reinforcing steel to air and moisture after about 50 years if the concrete cover is 50 mm or less. As a consequence of exposed reinforcing steel, the structural integrity and durability of the structure can be reduced in the long-term perspective.

Hassanzadeh (2010a) suggested that progressive damage to the concrete surface at the waterline is caused by interaction of multiple damage mechanisms. The dominating damage mechanism could not, however, be determined. According to the climatic conditions in Sweden, concrete at the waterline of hydraulic structures in fresh water bodies is primarily exposed to leaching, frost action and erosion by water and/or ice floes.

3.2 Internal Damage in 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 the same dams, spalling of concrete has been observed. In the latter case, damage was found in the vicinity of water leakage through cracks in the dams. None of the dams had been provided with heat insulating walls on the downstream side during the construction time.

3.2.1 Example 1

The crest length of the buttress dam at Storfinnforsen is 640 m and the maximum height is 40 m. The thickness of the upper part of the flat slab is 1.2 m while the lower part is 2.6 m. Concrete with a w/c-ratio of 0.5 was used in the flab slab, while the corresponding value for the concrete used in the buttresses was 0.6. The cement used was standard Portland cement (Limhamn Std). Construction work began in 1949 and the power plant was commissioned in 1954.

A large number of cracks in the flat slab were reported by Bergström and Nilsson (1962) less than eight years after the commissioning. Laboratory measurements showed that calcium were dissolved in the water leaking through the cracks. Frost damage was found only in a few cases and only in the vicinity of leaking dilatation joints.

About 30 years later, Fahlén and Näslund (1991) reported that the number of cracks was tripled and the average length of the cracks was doubled. Spalling of concrete was observed on the downstream face of the dam. The concrete cover was missing in several places and the bond between reinforcing steel bars and concrete was reduced. No evidence of corrosion of the reinforcing steel was found. On the upstream face, divers observed damaged areas between the maximum water level and some 10 to 12 m down. The damaged areas varied between 0.5 and 10 m^2 in size and they were up to 200 mm in depth.

Eriksson (1994) reported that up to 300 mm thick ice coatings were formed on the upstream face in winter. Formation of ice coatings 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 the winter.

In order to prevent the flat slab from freezing in winter, the dam was repaired and provided with heat insulating walls on the downstream side in the early 1990s.

3.2.2 Example 2

Construction work of the arch dam at Selsfors began in 1941 and the power plant was commissioned in 1944 (Figure 3-2 A). 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 3-2 B). In some cases, divers were able to remove pieces of concrete up to a depth of 150 mm.

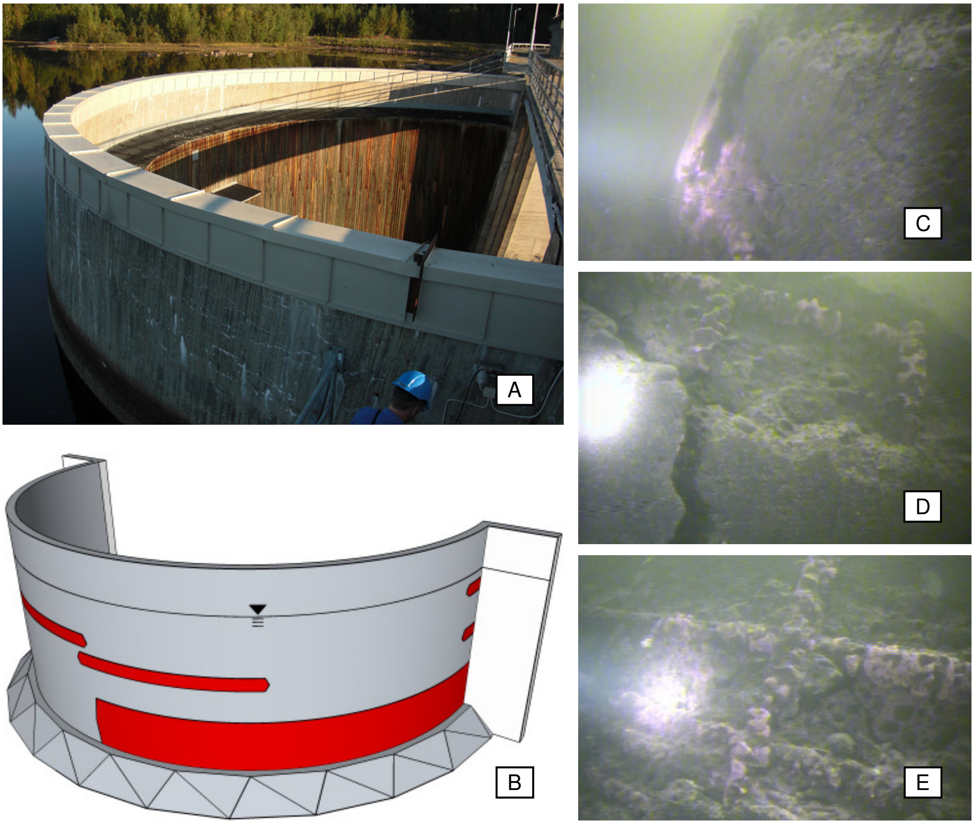

Figure 3-2. The greater part of the damage to the arch dam at Selsfors (A) was found on the lower part of the dam (B). Photos of corroding steel reinforcing bars and loose pieces of concrete on the upstream face (C-E). Photos from Skellefteå Kraft AB.

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

Photos taken during a recent inspection show the extent of damage to the upstream face (Figure 3-2 C-E). The concrete cover is missing in several places and steel reinforcing bars are visible.

3.2.3 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 3-3 C). 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 3-3 D). The concrete in the damaged areas was wet due to water leakage through cracks in the flat slab just above the damaged areas. No actions had been taken to repair the dam.

After about 70 years in service, 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 3-3 A-B). All loose pieces of concrete were flushed away by the water escaping through the hole. The reinforcing steel bars were seen from both sides of the flat slab.

3.2.4 Remarks

These three examples consider only thin concrete dams. Since the dams had not been provided with heat insulating walls on the downstream side during the construction time, one can assume that they had been frozen during the winter. The formation of ice on the upstream face far below the maximum water level in Example 1 confirms that assumption. The risk of frost damage is imminent when concrete of (probably) high moisture content is subjected to freezing.

Unfortunately, spalling of concrete on the upstream face of thin concrete dams can be difficult to discover from the dam's crest. In addition to these three examples of frost-damaged dams, there are probably more thin concrete dams with similar damage around the world.

Figure 3-3. A severely damaged buttress dam (C). The concrete cover was missing in some places in the vicinity of water leakage through cracks on the downstream face (D). A hole appeared in the flat slab in another place and water escaped flushing away loose pieces of concrete (A-B). Only the reinforcing steel was left.

3.3 Advances in Concrete Technology

Concrete, and particularly reinforced concrete, were new building materials in the early 20th century 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. In unreinforced concrete structures, such as solid gravity dams, the cement content was normally less than 200 kg/m^3 resulting in non-water tight concrete. In order to ensure water tightness of the water retaining structures, cement-rich concrete was used in the outermost layer facing water.

However, proper tamping of dry concrete mixes in narrow forms filled with reinforcing steel bars was hard to achieve. 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 w/c-ratio up to 1.0 were commonly used. The use of lean mixes with a high w/c-ratio led to almost immediate leaching of the concrete due to percolating water. The porosity and permeability of the concrete were thus increased when hydration products of the cement were dissolved and transported away.

In order to make the concrete less permeable, the cement content was increased to approximately 275-350 kg/m^3 in the late 1920s. The content of fine particles in the concrete mixes was also increased. The w/c-ratio was reduced to about 0.6. However, the risk of thermal cracking due to heat evolution during the cement hydration was instead increased. As a countermove, new cements were developed.

The low heat cement (Limhamn LH) developed by Forsén (1936) following a request from Vattenfall in the late 1920s must be mentioned. It should be noted in this context that the company Vattenfall was formerly known as Kungliga Vattenfallsstyrelsen (The Royal Board of Waterfalls) and later as Statens Vattenfallsverk (Swedish State Power Board). The low heat cement became the most used cement during the Swedish hydro power development.

Unfortunately, the workability of the fresh concrete was reduced when 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. Not until he added lathering albuminoids to the mix was the workability improved. Albuminoids were used for the first time in concrete by Vattenfall during the heightening of the 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, plasticizers 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 concrete technology for hydro power structures were made until the end of the major hydro power development era in the late 1970s.

From a general point of view, proper execution of concrete work in accordance with instructions resulted in most cases to improved durability of the concrete structures. However, the early 1940s may be an exception. Shortage of coal supplies due to the outbreak of the Second World War resulted in rationing of cement and subsequent development of the replacement cement (E-cement).

The E-cement was composed of about 50-70% Portland cement and 30-50% granulated blast furnace slag, silica or lime (Sandberg 1942). Eriksson (2002) reported that the performance of hydraulic structures built of concrete with E-cement varies greatly. The varying performance of the structures may depend on factors such as variations in the supplementary material, different cement producers, workmanship of different skills or variations in the climatic conditions.

3.4 Physical Properties of Concrete

3.4.1 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 (CSH), calcium aluminium hydrates (C_3A), calcium aluminium iron hydrates (C_4AF) and calcium hydroxide (CH) are formed around the cement grains. CH is also called Portlandite. 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 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 called capillary porosity.

3.4.2 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 great 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 increases with increasing w/c-ratio.

Air is entrapped in concrete during mixing operations. These air voids are called compaction voids and they are normally larger than 1 mm in size. However, 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.

3.4.3 Moisture Fixation in Concrete

In cement paste, mortar 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. Capillary condensation mostly takes place in capillary pores.

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 is dependent 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. This phenomenon is called capillary condensation. If the relative humidity is further increased, capillary condensation also takes place in larger pores.

3.4.4 Moisture Content of Concrete

The relative humidity (RH) 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. Sorption isotherms are often used to describe the relationship between physically bound water and the relative humidity of ambient air in the hygroscopic range (0 to 98% RH).

Above the hygroscopic range, the moisture content is increased due to capillary suction of water from external sources. Fagerlund (2006) reported that the moisture content above capillary saturation is increased due to dissolution of entrapped air in compaction voids and air voids. An absorption isotherm completed with moisture ranges is shown in Figure 3-4.

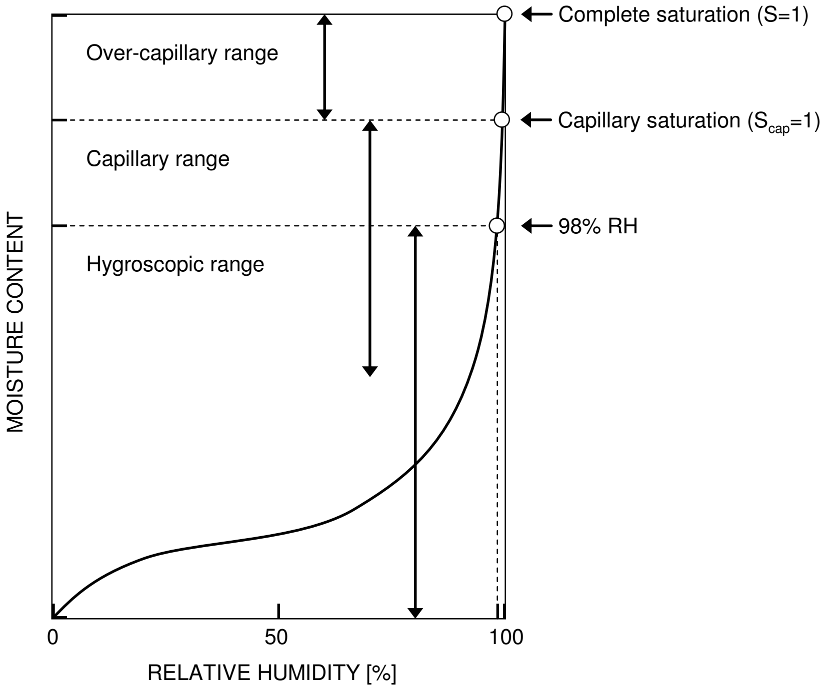

Figure 3-4. Absorption isotherm completed with moisture ranges. Graph from Fagerlund (2006).

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

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

where m_{wet} is the mass of the sample in the moist state, m_{cap} is the mass of the sample after capillary saturation and m_{105} is the mass of the sample in the dry state.

Above the capillary range, the moisture content of concrete can also 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 moist state, m_{sat} is the mass of the sample after saturation and m_{105} is the mass of the sample in the dry state.

3.4.5 Moisture Transport in Concrete

Moisture transport phenomena in concrete can be divided into diffusion and liquid (capillary) flow. Diffusion of water molecules is driven by the difference in water vapour content at isothermal conditions. 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 by the formula:

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

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_o is the atmospheric pressure, σ is the surface tension, θ is the contact angle between water and solid, and r is the pore radius.

Further, water can 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 moisture 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). The different types of moisture flows overlap each other and the driving potentials also differ. A conceptual model of the moisture flow through a concrete dam, partly based on Hedenblad (1994), is shown in Figure 3-5.

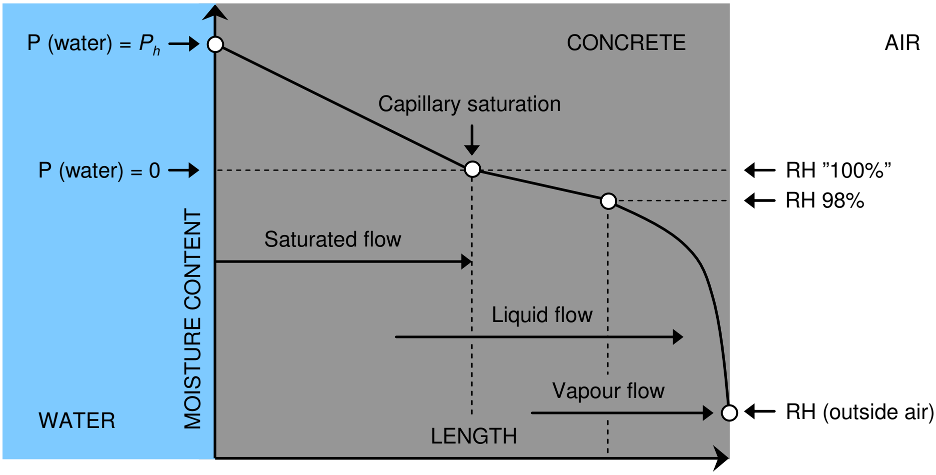

Figure 3-5. A conceptual model of the moisture flow through a concrete dam. The driving potential for moisture flow (saturated flow) close to the upstream face of the dam is the hydrostatic pressure pushing water into the concrete. However, at a certain depth from the upstream face, atmospheric pressure prevails and the moisture flow (liquid flow) is driven by capillary forces. Closer to the downstream face of the dam, the moisture flow (vapour flow) is driven by the difference in water vapour content. In reality, the different types of moisture flows overlap each other as shown in the figure.

In addition to hydrostatic pressure, pore water pressure and vapour content of air as the driving potentials, varying temperature gradients over the year also have effects on the moisture transport in concrete dams.

Wikström (2012) showed that concrete cylinders in direct contact with water and subjected to a temperature gradient in the range -5 °C to +10 °C absorbed more water at the hot side than cylinders in isothermal conditions (20 °C). No increase in water absorption at the hot side was noted when cylinders were subjected to a temperature gradient in the range +5 °C to +20 °C.

In another study, Sandström (2010) showed that concrete specimens subjected to alternating freezing and thawing conditions (-20 °C to +20 °C) absorbed more water than specimens in isothermal conditions (+18 °C).

3.4.6 Permeability of Concrete

The capillary porosity is continuous in young concrete. Hydration of cement increases the amount of cement gel, whereas the capillary porosity is reduced. 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.

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 3-6.

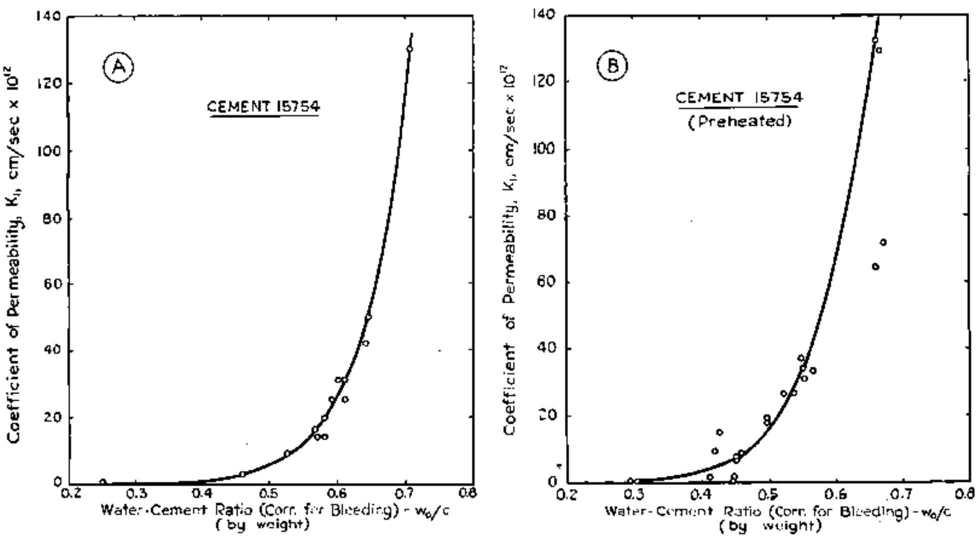

Figure 3-6. Relationships between hydraulic conductivity and w/c-ratio for mature cement paste. Graphs from Powers et al (1954).

Also the interfacial transition zone (ITZ) around aggregate particles is regarded by Leemann et al (2006) as a 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 great impact on the durability of concrete structures and especially of hydraulic structures subjected to hydrostatic pressure, frost action and aggressive agents.

As previously mentioned, gel pores, capillary pores, compaction voids and air voids can be found 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 is called open porosity (V_{po}). The open porosity is given by the formula:

$$V_{po} = \frac{m_{sat} - m_{105}}{m_{sat} - m_{sub}} \qquad (8)$$

where m_{sat} is the mass of the sample after 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.

3.5 Frost Action

3.5.1 Frost Damage Mechanisms

Powers (1945) stated that hardened concrete subjected to frost action can be damaged either by scaling or internal damage. Scaling deteriorates the concrete surface, whereas internal damage lowers the compressive and tensile strength of the concrete. Powers proposed the hydraulic pressure theory to explain the mechanism of frost damage. The theory was based on the fact that the volume of water expands by about 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.

About the same time as Powers presented his theory regarding frost damage to concrete, Collins (1944) presented the macroscopic ice lens growth theory. The latter was proposed 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 also poor quality concrete can 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.

Partly based on the fact that water has different freezing temperatures in pores of different sizes, the microscopic ice lens growth theory was proposed by Powers and Helmuth (1953). 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.

Over the years, several theories have been proposed to theoretically explain frost damage. The osmotic pressure theory and the glue spall theory are two more examples. Apart from the theories of frost damage mechanisms, Fagerlund (1977) showed that severe damage occurs in all cases upon freezing if the moisture content exceeds the critical degree of saturation (S_{cr}) at a specific temperature.

A summary of frost damage mechanisms with regard to scaling is presented in Paper I. The theory of frost heave in soils and macroscopic ice lens growth in concrete is summarized in Paper II.

3.5.2 Frost Resistance

When air entraining agents are used in concrete, the frost resistance is improved. 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 pore size distribution, distances between the air voids and volume of entrained air. The distance between two air voids is called the spacing factor. A summary about frost resistance of concrete is presented in Paper I.

3.5.3 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 voids and air voids (Figure 3-4). In the long-term perspective, the frost resistance of concrete can be reduced since it is dependent on the air content of concrete.

According to Janz (2000), there is a lack of knowledge about moisture transport in the over-capillary range in spite of the fact that several durability problems occur in concrete with moisture content above capillary saturation. To highlight the importance of moisture content on the risk of frost damage, Fridh (2005) showed that the moisture content has greater impact on the frost resistance of concrete than the w/c-ratio and air content have.

Freezing of air entrained concrete with high moisture content causes a greater amount of damage than freezing of non-air entrained concrete with the same moisture content. The reason in this case is that there is more freezable water in air entrained concrete, since also the air voids are completely or partially filled with water. Hence, the diffusion rate of air out of the air voids and eventually out of the material determines the time (t_{cr}) until the critical degree of saturation (S_{cr}) prevails, see Figure 3-7.

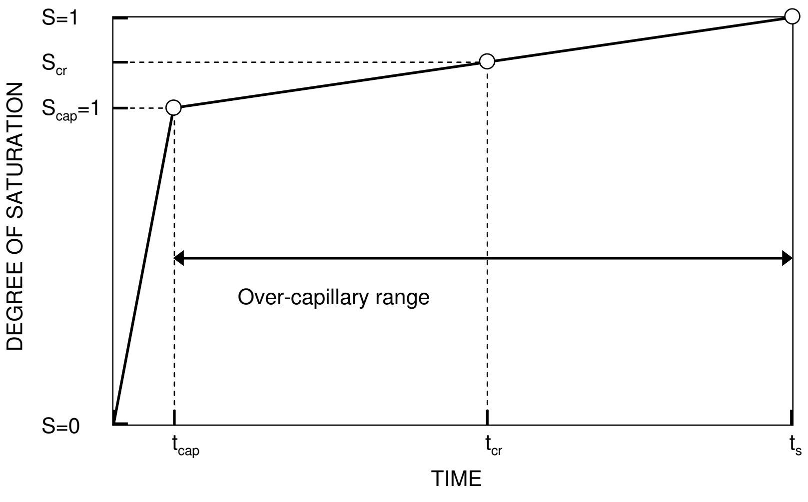

Figure 3-7. Water absorption of concrete as a function of time. The critical degree of saturation (S_{cr}) prevails at the critical time (t_{cr}).

3.6 Interacting Deterioration Processes

3.6.1 Synergy

Synergy is defined as the interaction of two or more elements, which together produce an effect greater than the sum of their individual effects.

3.6.2 Leaching

All hydration products of Portland cement are soluble in water to varying degrees. The process of dissolving calcium (Ca^{2+}) in water is called lime leaching or simply leaching. The most soluble hydration product is calcium hydroxide (CH). Lime is also dissolved from the other hydration products, such as CSH, C_3A and C_4AF. However, as long as there is CH left, lime from the other hydration products is dissolved to a much lesser extent. The rate at which lime is dissolved in water is dependent on the aggressiveness of water and the permeability of concrete.

Ekström (2003) studied the effects of leaching of concrete in hydro power dams. Besides the effects of percolating water, he also studied the effects of leaching from the concrete surface. Concrete specimens were placed in a tank containing de-ionized water for about two years. Measurements of the remaining concentration of calcium in the specimens showed that leaching of lime was greater close to the surface than deeper in the specimen.

3.6.3 Erosion

Erosion of concrete in hydro power structures in Sweden is primarily caused by continued water flow and ice abrasion. Abrasive wear from particles in the water is rare since the water in Swedish rivers carries very small amounts of sediments.

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 abrasion rate is increased with increasing contact pressure and decreasing ice temperature. However, the strength of concrete was found to have the greatest impact on the resistance to ice abrasion. Both the bond to aggregate and the frost resistance of concrete were improved when high strength concrete was used. Also the use of supplementary cementitious materials, such as blast furnace slag and silica, improved the resistance to ice abrasion.

In an overview of ice abrasion data from test methods and field studies, Møen et al (2007) concluded that ice sliding against concrete structures causes more abrasion than ice crushing against the structures.

3.6.4 Concrete Swelling due to Chemical Reactions

The use of alkali-reactive aggregate, exposure to sulphate dissolved in water or delayed ettringite formation are some examples of when chemical reactions may cause swelling and destructive cracking in concrete. With regard to hydro power structures in Sweden, alkali-aggregate reaction (AAR) may be of some interest.

Two forms of AAR are known – alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). The latter is rare since aggregate susceptible to this phenomenon is usually unsuitable for concrete. However, ASR may occur if aggregate containing reactive silica materials is used in the concrete. Reactive aggregate will react with alkali hydroxides (sodium and potassium) to form a gel that swells as it absorbs water. Hence, reactive aggregate is unsuitable for use in hydro power structures.

However, according to Fagerlund (2002), the susceptibility to ASR can be reduced by using low alkali cements with a total content of alkalis not above 0.6%. Field observations indicate that the choice of cement is important. The durability of some hydro power structures built with concrete containing reactive aggregate coming from a certain location seems to be dependent on the type of cement used. After about 50 years, no signs of cracking caused by chemical reactions can be found in the structures in which low alkali cement was used. On the contrary, extensive cracking of the concrete can be observed in the structures in which standard cement was used.

3.7 Knowledge Gaps

As shown in Chapter 3, the durability of concrete in hydro power structures is mostly dependent on concrete quality in terms of w/c-ratio and frost resistance. However, it is still not fully known exactly how concrete in hydraulic structures is deteriorated and how different damage mechanisms interact. Also the effects of long-term submersion of air entrained concrete in water are not fully known.

With regard to the effects of frost action, the frost resistance of concrete is of the greatest importance for the durability of concrete in hydraulic structures. The uncertainty of how concrete in hydraulic structures is deteriorated by frost action together with the suspicion that the frost resistance can be reduced over time has led to three questions, presented in Section 1.2. The questions are repeated below:

- Which deterioration processes cause progressive damage to the concrete surface at the waterline of hydraulic structures?

- What are the conditions for concrete spalling in 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 at different depths?

The research work conducted in this study with regard to these three questions is presented in Chapter 4, 5, 6 and 7.

4 Frost Resistance of Concrete at the Waterline

4.1 Background

A laboratory test method was developed by Persson and Rosenqvist (2009) in order to assess the frost resistance of concrete at the waterline of hydro power structures. The test method corresponds to prevailing climatic conditions at the waterline of hydro power structures in cold climates, see Section 2.3 and 3.1.

Standardized test methods, such as ASTM C672, CDF and SS 13 72 44, were all developed in order to primarily determine the scaling resistance of horizontal concrete surfaces, such as concrete roads and pavements. Hence, the standardized test methods were not considered appropriate for assessing the scaling resistance of concrete at the waterline of hydraulic structures.

Two concrete mixes were produced in order to verify the test method; non-air entrained concrete with w/c-ratio 0.65 and air-entrained concrete with w/c-ratio 0.45. A CEM II Portland-limestone cement (Byggcement) was used in the study. The specimens with w/c-ratio 0.65 were expected to suffer superficial damage at the waterline, whereas the specimens with w/c-ratio 0.45 were not. Progressive damage to the concrete surface at the waterline was observed after 50 freeze-thaw cycles in the former case, whereas no damage was observed in the latter case.

The laboratory test method developed by Persson and Rosenqvist is presented in Paper I. Also the results obtained from the specimens used in order to verify the test method are presented in Paper I.

4.2 Materials

In this study, the frost resistance of three concrete mixes (w/c-ratio 0.54, 0.62 and 0.70) was assessed according to the laboratory test method presented in Paper I. The mix proportions were selected in accordance with Vattenfall's handbooks, published between 1942 and 1972. In this context, it should be noted that the company Vattenfall was formerly known as Kungliga Vattenfallsstyrelsen (1942) and (1945), and Statens Vattenfallsverk (1956) and (1972).

The proportions of the concrete mixes are presented in Table 4-1 and the fresh properties are presented in Table 4-2. In this study, Anläggningscement was used instead of Byggcement. Anläggningscement is a CEM I Portland cement. The clinker phase composition of the cement is relatively similar to the Limhamn standard cement, which, together with the Limhamn low heat cement, was often used in the construction of hydro power structures, see Section 3.3.

Table 4-1. Proportions of the concrete mixes.

w/c	**Cement** [kg/m³]	**0–1 mm** [kg/m³]	**1–4 mm** [kg/m³]	**0–8 mm** [kg/m³]	**4–8 mm** [kg/m³]	**8–16 mm** [kg/m³]
0.70	285	310	-	658	-	857
0.62	325	335	65	440	110	835
0.54	300	320	75	300	200	950

The concrete mix with w/c-ratio 0.62 is typical for concrete used in water retaining structures during the 1930s and 1940s, whereas the concrete mix with w/c-ratio 0.54 is typical for concrete used approximately between 1950 and 1970. Concrete with w/c-ratio up to 0.70 has occasionally been used in hydraulic structures not subjected to hydrostatic pressure.

Table 4-2. Properties of the fresh concrete.

w/c	**Air Content** [%]	**Slump** [mm]	**Density** [kg/m³]
0.70	2.1	30	2373
0.62	2.6	110	2356
0.54	4.1	20	2363

The hardened concrete properties, such as the compressive strength at 28 and 91 days, are presented in Table 4-3. Also the porosity and the degree of saturation (S) at capillary saturation (S_{cap}), according to equation 3, are presented in the table.

Table 4-3. Properties of the hardened concrete.

w/c	Strength 28 D [MPa]	Strength 91 D [MPa]	Porosity [-]	S at S_{cap} [-]
0.70	37.3	51.8	0.14	0.86
0.62	44.6	58.9	0.16	0.84
0.54	45.9	58.2	0.15	0.77

4.3 Method

The laboratory test method presented in Paper I is termed the frost test in this context. Two changes were made in the 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. 7.5 hours of freezing and 4.5 hours of thawing. In total, the specimens were subjected to 112 freeze-thaw cycles.

The specimens were partially submerged in water two weeks prior to the start of the frost test. At start (week 0), the moisture content was determined in one specimen. The procedure to determine the moisture content is described in Paper I. During the test period, the moisture content of the specimens was determined by taking one specimen out of the freezer every second week (week 2, 4, 6 and 8). At the end of the test period (week 8), the moisture content was also determined in a reference specimen kept partially submerged in water at constant temperature (10 °C) during the test period.

After the test period, the splitting tensile strength of the remaining specimens used in the frost test was determined according to SS-EN 12390-6; see Svensk Standard (2009). The results were compared with results from reference specimens kept dry at +20 °C. All specimens were partially submerged in water at 20 °C during a period of four weeks prior to the splitting tensile strength test.

The scaling resistance of the three concrete mixes was determined according to SS 13 72 44; see Svensk Standard (2005). The cut surface was exposed to either de-ionized water or salt water (3% NaCl) during the frost test. In addition to tests on the cut surface, the scaling resistance of the outer surface was also determined.

4.4 Results

4.4.1 w/c-ratio 0.70

Only minor damage to the concrete surface of the specimens with w/c-ratio 0.70 was observed below and at the waterline after 112 freeze-thaw cycles. The damage was concentrated to a band of 20-30 mm width below the waterline (Figure 4-1). All specimens showed similar damage.

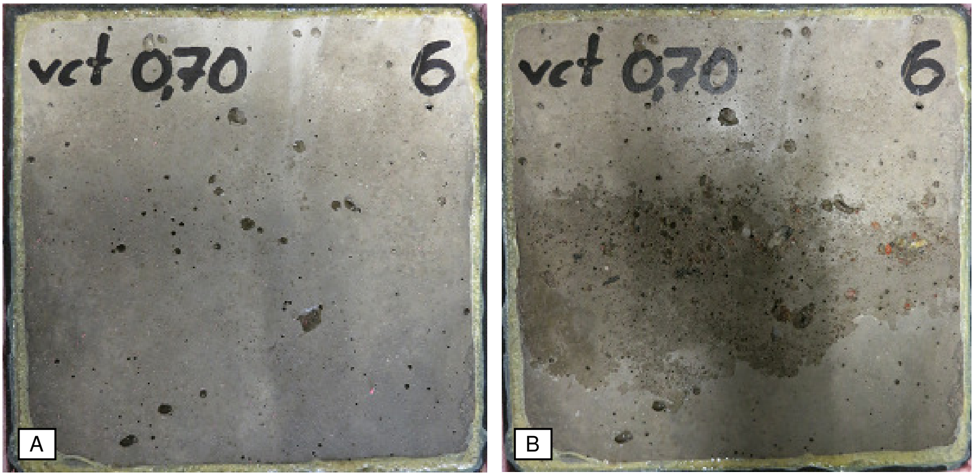

Figure 4-1. Specimen (w/c-ratio 0.70) before (A) and after (B) the test.

In spite of varying results from specimen to specimen, capillary saturation (S=0.86) was obtained in the concrete below the waterline in the specimens subjected to the frost test within two weeks after the start. Also in the concrete above the waterline, capillary saturation was obtained. However, the degree of saturation of concrete above the waterline was somewhat lower in the reference specimen kept at +10 °C during the test period. Results from the measurements of the degree of saturation (S) are presented in Figure 4-2.

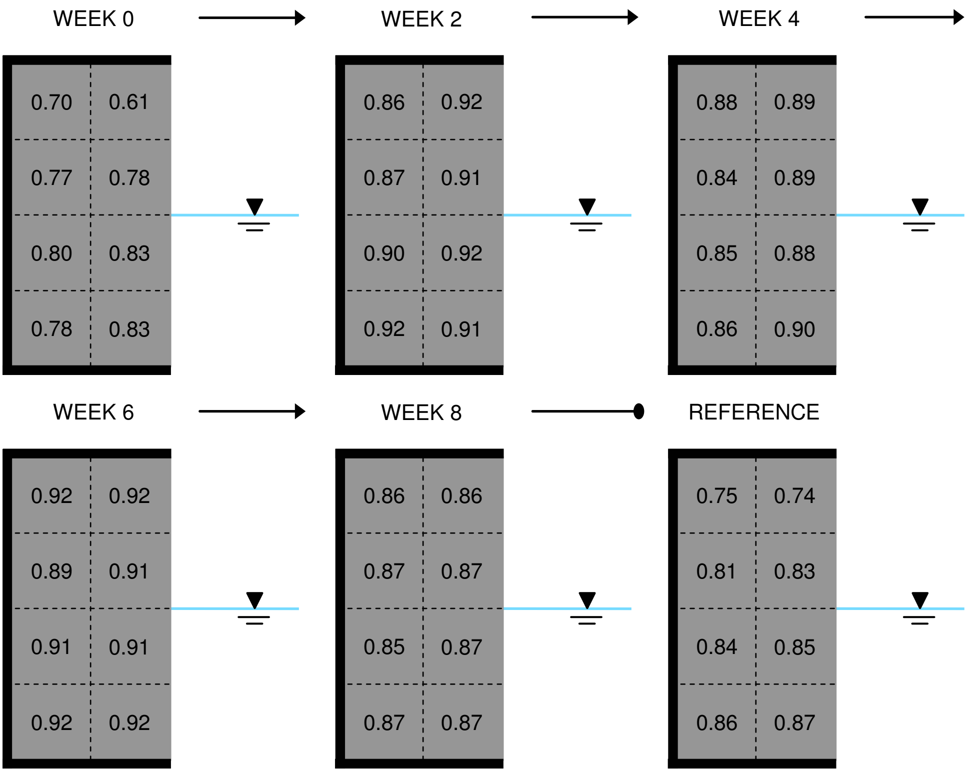

Figure 4-2. Degree of saturation of specimens (w/c 0.70) subjected to the frost test in comparison with the reference specimen kept at +10 °C during the test period.

4.4.2 w/c-ratio 0.62

Minor damage to the concrete surface of the specimens with w/c-ratio 0.62 was observed at the waterline by the removal of small flakes of cement paste after 112 freeze-thaw cycles (Figure 4-3). The amount of damage varied somewhat between the specimens. Damage to the concrete surface could not be observed below the waterline on any of the specimens.

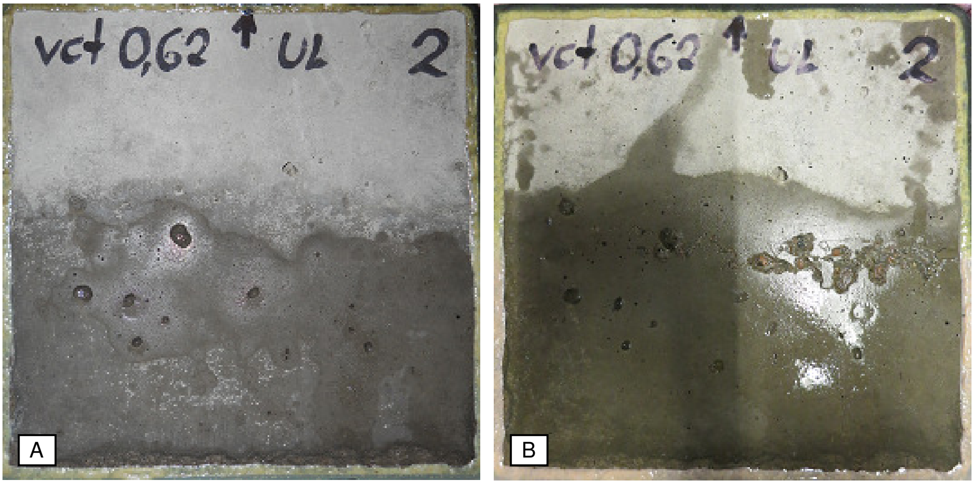

Figure 4-3. Specimen (w/c-ratio 0.62) before (A) and after (B) the test.

Also regarding the specimens with w/c-ratio 0.62, the degree of saturation varied from specimen to specimen. The moisture content of concrete below the waterline slowly increased during the test period. The same trend applied to concrete above the waterline. Capillary saturation (S=0.84) was not obtained either above or below the waterline during the test period. However, the results indicate that the moisture content of concrete above the waterline was close to capillary saturation at the end of the test period.

On the contrary, the moisture content of concrete in the reference specimen kept at +10 °C decreased during the test period. Hence, the drying rate was higher than the absorption rate in isothermal conditions. Results from the measurements of the degree of saturation are presented in Figure 4-4.

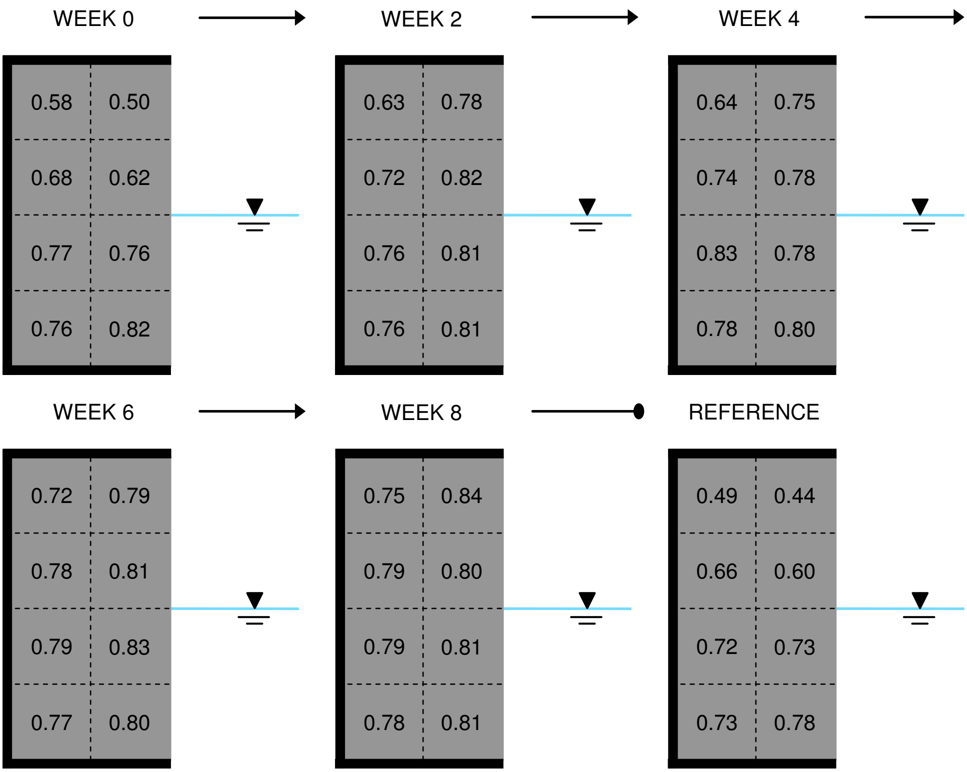

Figure 4-4. Degree of saturation of specimens (w/c 0.62) subjected to the frost test in comparison with a reference specimen kept at +10 °C during the test period.

4.4.3 w/c-ratio 0.54

No damage to the concrete surface could be observed on any of the specimens with w/c-ratio 0.54 after 112 freeze-thaw cycles (Figure 4-5). The results on the measurements of the moisture content indicate that capillary saturation (S=0.77) was obtained within two weeks after the start in the specimens subjected to the frost test. On the contrary, the degree of saturation of concrete in the reference specimen kept at +10 °C decreased during the test period. Also in the case of concrete with w/c-ratio 0.54, the drying rate was higher than the absorption rate in isothermal conditions. Results from the measurements of the degree of saturation are presented in Figure 4-6.

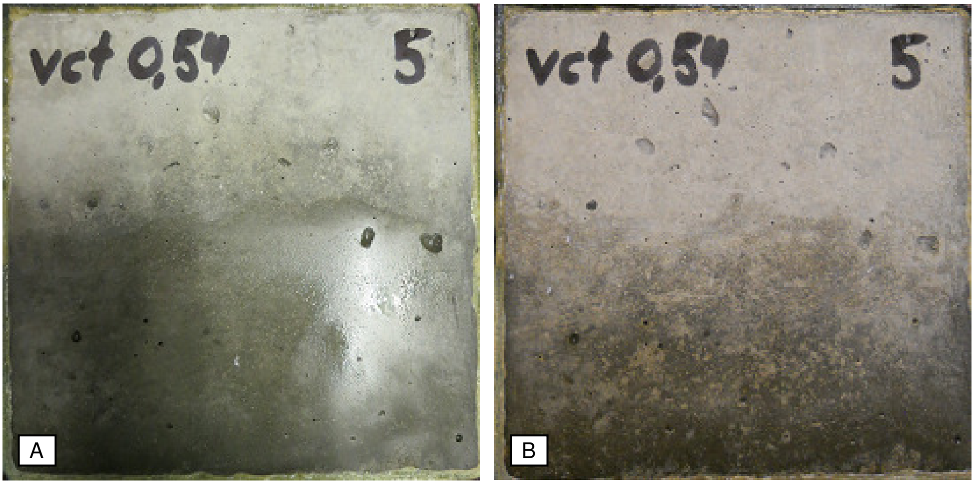

Figure 4-5. Specimen (w/c-ratio 0.54) before (A) and after (B) the test.

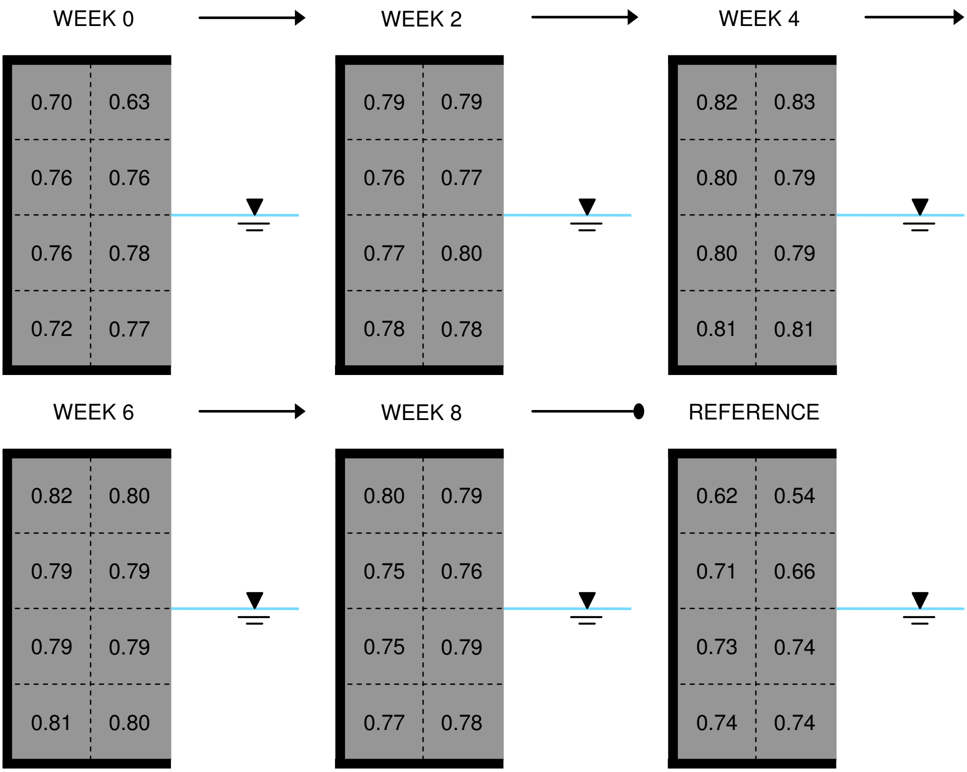

Figure 4-6. Degree of saturation of specimens (w/c 0.54) subjected to the frost test in comparison with a reference specimen kept at +10 °C during the test period.

4.4.4 Splitting Tensile Strength

After the end of the frost test, the splitting tensile strength of specimens subjected to the frost test was compared with the splitting tensile strength of reference specimens kept dry at +20 °C. The splitting tensile strength was determined for all three concrete mixes. All the specimens intended for use in the test were partially submerged in water four weeks prior to the test. Before the test, the specimens were split at the waterline into two equal parts of size 150x70x70 mm. The upper part is called 'above waterline', whereas the lower part is called 'below waterline'.

The splitting tensile strength was determined according to SS-EN 12390-6; see Svensk Standard (2009). The splitting tensile strength (f_{ct}) is given by the formula:

$$f_{ct} = \frac{2 \cdot F}{\pi \cdot L \cdot d} \quad (9)$$

where F is the maximum load (N), L is the length of line of contact of the specimen (mm) and d is the designated cross-sectional dimension (mm).

The results from the splitting tensile strength test are presented in Table 4-4. A slight increase in the splitting tensile strength below the waterline was obtained for all concrete mixes subjected to the frost test. A slight increase in the splitting tensile strength was also obtained above the waterline for the concrete mix with w/c-ratio 0.54. However, the results indicate internal damage above the waterline in the concrete mixes with w/c-ratio 0.62 and 0.70. The splitting tensile strength was reduced by about 20 to 25% in comparison with the reference specimens.

Table 4-4. Splitting tensile strength of concrete specimens subjected to the frost test (Test) in comparison to reference specimens (Ref). The specimens were split at the waterline into two parts – below waterline (BW) and above waterline (AW).

w/c	**BW Ref** [MPa]	**BW Test** [MPa]	**Strength** [%]	**AW Ref** [MPa]	**AW Test** [MPa]	**Strength** [%]
0.70	4.1	4.3	105	4.3	3.3	76
0.62	3.7	3.9	105	4.4	3.5	79
0.54	4.6	4.9	105	4.1	4.8	115

4.4.5 Scaling Resistance

The scaling resistance of the three concrete mixes was determined according to SS 13 72 44; see Svensk Standard (2005). The first set of specimens was exposed to de-ionized water on the cut surface during the test period of 56 days. The second set of specimens was exposed to de-ionized water on the outer surface, while the third set of specimens was exposed to salt water (3% NaCl) on the cut surface. A set of specimens consists of four specimens. The results are presented in Table 4-5. The grades used to classify the scaling resistance (*Very good, Good, Acceptable* and *Unacceptable*) are stated in the standard.

The scaling resistance of the cut surface in the presence of de-ionized water was *Very good* for all concrete mixes. The same grade applied to the outer surface with the exception of the concrete mix with w/c-ratio 0.62 (*Good*). The scaling resistance of three of the four specimens with w/c-ratio 0.62 was *Very good*, whereas 74% of the total weight loss was collected from the fourth specimen.

Only the concrete mix with w/c-ratio 0.54 can be classified as *Very good* when the cut surface was exposed to salt water (3% NaCl). The grade for the concrete mix with w/c-ratio 0.62 was *Acceptable*, whereas it was *Unacceptable* for the concrete mix with w/c-ratio 0.70.

Table 4-5. The scaling resistance of concrete mixes with w/c-ratio 0.54, 0.62 and 0.70 determined according to SS 13 72 44.

		w/c 0.54	**w/c 0.62**	**w/c 0.70**
Fresh water	Outer surface	0.02 kg/m^2	0.12[a] kg/m^2	0.05 kg/m^2
(de-ionized)		*Very good*	*Good*	*Very good*
Fresh water	Cut surface	0.01 kg/m^2	0.01 kg/m^2	0.02 kg/m^2
(de-ionized)		*Very good*	*Very good*	*Very good*
Salt water	Cut surface	0.09 kg/m^2	0.96 kg/m^2	>2.78[b] kg/m^2
(3% NaCl)		*Very good*	*Acceptable*	*Unacceptable*

[a] – 74% of the total weight loss was collected from one of four specimens tested.
[b] – One specimen was destroyed before 42 days and another one before 56 days.

4.5 Discussion and Conclusions

The results obtained from the experiments showed that the scaling resistance of air entrained concrete with w/c-ratio 0.54 in the presence of de-ionized water was *Very good*. Also the scaling resistance of concrete with w/c-ratio 0.62 and 0.70 in the presence of de-ionized water was classified as *Very good* according to the test method SS 13 72 44.

When the frost resistance was assessed according to the laboratory test method presented in Paper I, indications of internal damage above the waterline were obtained for concrete with w/c-ratio 0.62 and 0.70. Internal damage due to frost action occurs when the critical degree of saturation (S_{cr}) is reached and the concrete freezes. Internal damage in the specimens above the waterline can be explained by a greater amount of freezable water due to lower temperatures in the concrete above the waterline during the freezing phase of the cycle.

The measurements of the moisture content showed that the water absorption was increased when the specimens were subjected to freeze-thaw cycles. On the contrary, the reference specimens partially submerged in water and kept at 10 °C were drying out during the test period and especially above the waterline.

Perhaps, the moisture content of concrete in hydraulic structures increases during the winter and decreases during the summer. According to the results obtained in this study, the risk of internal damage above the waterline decreases with decreasing w/c-ratio and increasing air content. Still, the overall risk of internal damage above the waterline of hydraulic structures is unknown.

Minor damage to the concrete surface below and at the waterline was observed for concrete with w/c-ratio 0.62 and 0.70. The amount of damage obtained after 112 freeze-thaw cycles was less than it was for concrete with w/c-ratio 0.65 after 51 freeze-thaw cycles. However, the latter concrete mix was used only to verify the test method and it is not typical for concrete used in water retaining structures. The major difference between the concrete mixes was the cement type used; Anläggningscement (CEM I Portland cement) in the former case and Byggcement (CEM II Portland-limestone cement) in the latter case. The results indicate that the frost resistance of concrete is reduced when Byggcement is used.

The amount of damage obtained after 112 freeze-thaw cycles for concrete with w/c-ratio 0.62 and 0.70 is most likely too small to be able to conclude that frost action solely accounts for progressive damage to the concrete surface at the waterline of hydraulic structures, see Section 3.1. Further, the lack of damage to the concrete surface of the specimens with w/c-ratio 0.54 does not agree with observations of damage to hydraulic structures.

According to the results obtained in this study, progressive damage to the concrete surface at the waterline of hydraulic structures is caused not only by the effects of frost action. The effects of other deterioration processes, such as leaching and abrasion are also likely to cause damage to the concrete surface at the waterline.

5 Interaction between Leaching, Frost Action and Abrasion

5.1 Background

The results from the study of the frost resistance of concrete at the waterline (see Chapter 4) did not give a satisfactory explanation of how progressive damage to the concrete surface at the waterline of hydraulic structures occurs, see Section 3.1.

A possible scenario of deterioration of concrete at the waterline is that leaching of the concrete surface takes place during the snowmelt runoff period. The concrete surface is thus more susceptible to frost action. During the following winter, the surface layer is damaged by frost action and later removed due to ice abrasion. During the next snowmelt runoff period, the process starts all over again.

Hassanzadeh (2010b) studied the scaling resistance of concrete from the spillway section of Stenkullafors power plant. The scaling resistance was determined according to the test method SS 13 72 44; see Svensk Standard (2005). It was shown that the scaling resistance of the outer surface was remarkably reduced compared with the cut surface. The causes of the reduced scaling resistance of the outer surface could not, however, be determined. Bleeding and/or leaching of the outer surface were suggested as possible causes of the reduced scaling resistance.

In this study, Pham and Terzic (2013) primarily studied the effects of leaching on the scaling resistance of concrete and secondarily the effects of abrasion.

5.2 Materials

Concrete mixes with w/c-ratio 0.54 and 0.62 were used to study the effects of leaching and abrasion on the scaling resistance. The proportions of the mixes are presented in Table 4-1. A CEM I Portland cement (Anläggningscement) was used. The fresh and hardened properties of the concrete mixes are presented in Table 5-1. The differences in the properties are due to the fact that additional batches were produced for each mix.

Table 5-1. Properties of the fresh and hardened concrete.

w/c	Air Content [%]	Slump [mm]	Density [kg/m³]	Strength 28 D [MPa]
0.62	1.3	80	2375	40.2
0.54	4.1	25	2350	43.0

5.3 Method

In order to study the effects of leaching, frost action, abrasion and combinations of these on the deterioration of the concrete surface, sets of three specimens were subjected to different combinations of deterioration processes:

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

The specimens were produced according to the test method SS 13 72 44, see Svensk Standard (2005). The specimens were subjected to freezing and thawing in the presence of de-ionized water according to the procedure described in the test method. The specimens exposed to all three deterioration processes (F+L+A) were subjected to one week of leaching, then a second week of frost action and finally abrasion. This procedure was repeated four times.

To study leaching phenomena in concrete, two basic approaches can be used; (1) long-term exposure to de-ionized water or (2) short-term exposure to aggressive agents, such as acids. In this study, leaching of calcium from the concrete surface was facilitated when the specimens were submerged in de-ionized water at pH 4 and pH 7. The desired pH-values were maintained by automatic addition of nitric acid (HNO_3). The test setup was based on work by Planel et al (2006) and Rozière et al (2009). They accelerated leaching of calcium by addition of nitric acid.

Following the week of frost action and before submersion in the de-ionized water, steel brushes of size 50x10 mm were used to cause abrasive action to the concrete surface. The concrete surface was carefully brushed ten times back and forward.

5.4 Results

According to the test method SS 13 72 44, the scaling resistance of concrete with w/c-ratio 0.54 and 0.62 was *Very good*. Regarding the specimens subjected to different combinations of deterioration processes, only results from the specimens subjected to leaching in water at pH 4 are presented in this section. The effects of leaching in water at pH 4 on the scaling resistance were greater than those caused by leaching in water at pH 7.

The effects of leaching, frost action and abrasion were quantified as the weight of loose materials collected from the concrete surface of each set of specimens. The accumulated weight loss of concrete specimens with w/c-ratio 0.62 subjected to different combinations of deterioration processes is presented in Figure 5-1.

The least amount of loose materials was collected from the specimens subjected to frost action (F). A slight increase in the amount of loose materials was noted for the specimens also subjected to abrasion (F+A). The amount of loose materials was remarkably increased for the specimens subjected to leaching in water at pH 4 prior to frost action (F+L). However, the greatest amount of loose materials was collected from the specimens subjected to all three deterioration processes (F+L+A).

The accumulated weight loss of concrete specimens with w/c-ratio 0.54 subjected to different combinations of deterioration processes is presented in Figure 5-2. No loose materials 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). As for the specimens with w/c-ratio 0.62, there was an increase in the amount of loose materials collected from the specimens subjected to leaching in water at pH 4 prior to frost action (F+L). Also in this case, the greatest amount of loose materials was collected from the specimens subjected to all three deterioration processes (F+L+A).

The accumulated weight loss of the specimens subjected to all three deterioration processes (F+L+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 in water at pH 4 and abrasion (L+A). The accumulated weight loss of the specimens with w/c-ratio 0.54 and 0.62 is presented in Figure 5-3.

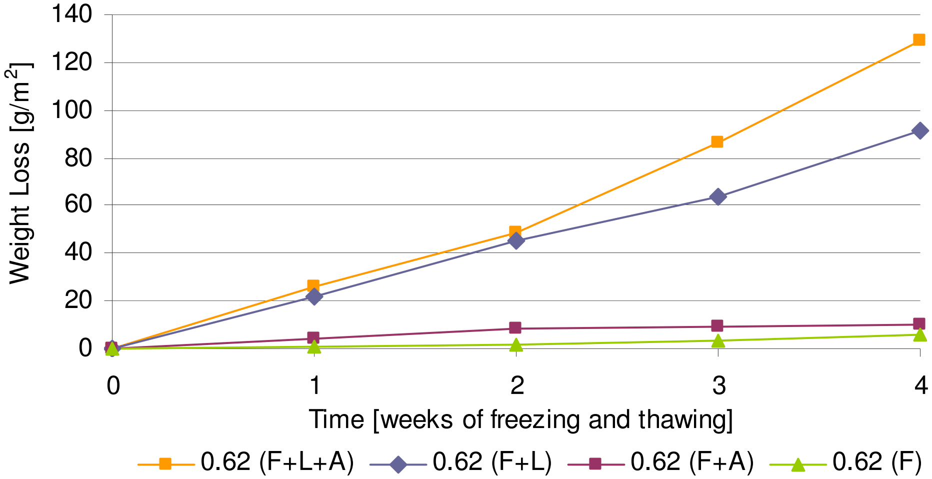

Figure 5-1. Accumulated weight loss of specimens with w/c-ratio 0.62 subjected to different combinations of the deterioration processes; frost action (F), leaching in water at pH 4 (L) and abrasion (A).

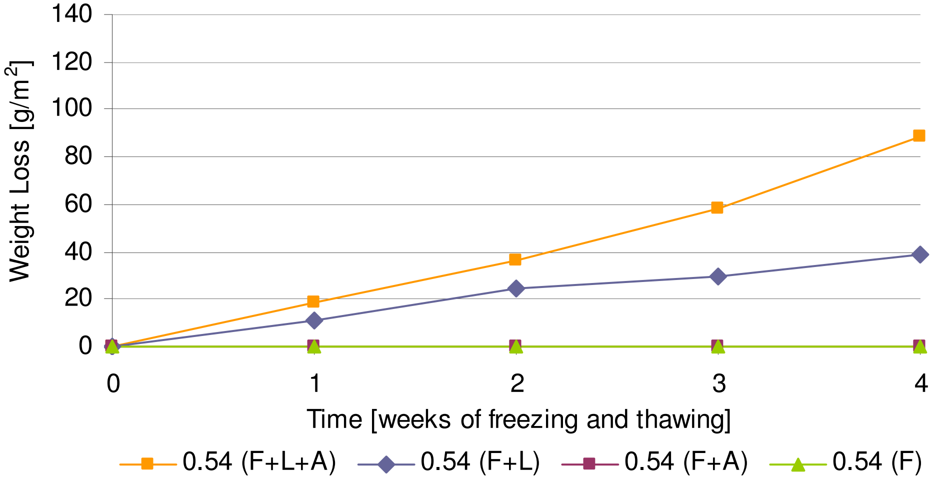

Figure 5-2. Accumulated weight loss of specimens with w/c-ratio 0.54 subjected to different combinations of the deterioration processes; frost action (F), leaching in water at pH 4 (L) and abrasion (A).

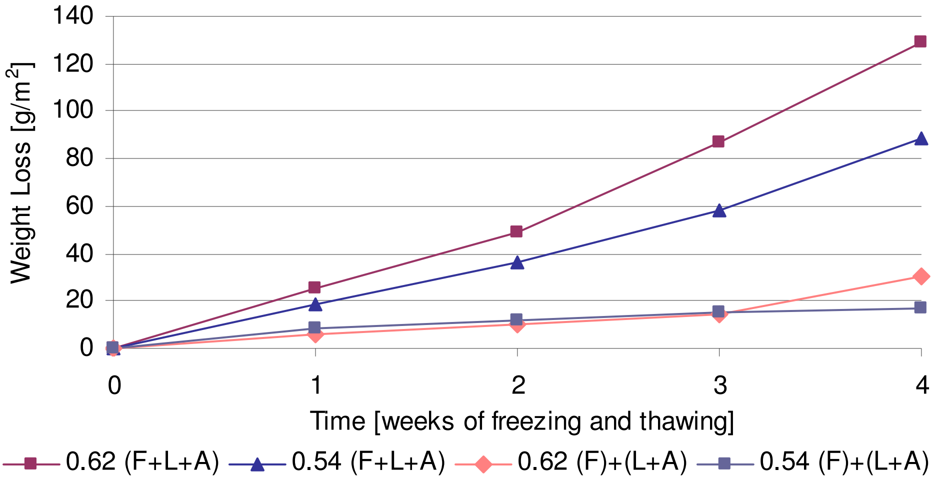

Figure 5-3. Accumulated weight loss of the specimens subjected to all three deterioration processes (F+L+A) compared to the sum of weight loss from the specimens subjected to frost action (F) together with the specimens subjected to leaching and abrasion (L+A). The differences in weight loss indicate synergy between the deterioration processes.

The difference in weight loss between the specimens subjected to (F+L+A) and the specimens subjected to (F)+(L+A) indicates synergy between the deterioration processes. Also the difference in weight loss between (F+L+A) and (F)+(L+A) was greater for the specimens with w/c-ratio 0.62 compared with the specimens with w/c-ratio 0.54. The use of concrete with low w/c-ratio consequently increases the resistance to the effects of interacting deterioration processes.

The concentrations of ions in the water used for leaching of the concrete surface were determined every week by chemical analysis. The concentrations of calcium (Ca), silicon (Si), aluminium (Al), iron (Fe), potassium (K), magnesium (Mg), sodium (Na) and sulphur (S) were determined.

The leaching losses of calcium were twice as high in water at pH 4 as in water at pH 7, whereas the smaller leaching losses of silicon were 1.5 times as high in water at pH 4 as in water at pH 7. The leaching losses of silicon show that there is partial dissolution of CSH in water at both pH 4 and pH 7. However, leaching in water at pH 4 does not significantly change the ratio between the losses of calcium and silicon in comparison with leaching in water at pH 7. Hence, these results indicate that exposure to water at pH 4 only accelerates the leaching process.

The final appearance of the concrete surface of specimens subjected to different combinations of deterioration processes is shown in Figure 5-4. In accordance with the obtained weight losses, the surface of the specimens subjected to frost action (F) remained intact, whereas the surface of the specimens subjected to all three deterioration processes (F+L+A) was deteriorated. The amount of damage to the concrete surface was greater for concrete with w/c-ratio 0.62 in comparison with concrete with w/c-ratio 0.54.

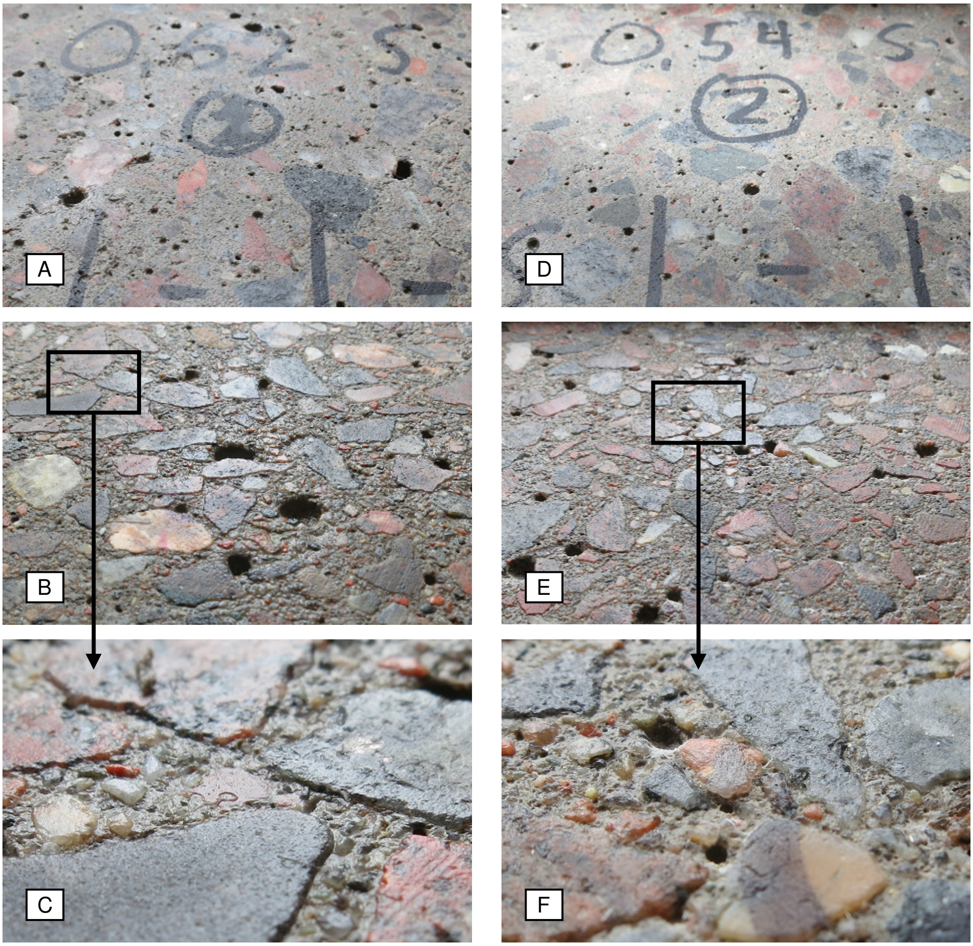

Figure 5-4. Cut surface (w/c 0.62) subjected to (F) in Fig. A compared with the cut surface subjected to (F+L+A) in Fig. B. Enlargement of the area marked by the rectangle in Fig. C. Cut surface (w/c 0.54) subjected to (F) in Fig. D compared with the cut surface subjected to (F+L+A) in Fig. E. Enlargement of the area marked by the rectangle in Fig. F.

5.5 Discussion and Conclusions

According to the results obtained by Pham and Terzic (2013), the effects of leaching on the scaling resistance of concrete are greater than the effects of abrasion. When the concrete surface has been weakened by leaching, the scaling resistance is significantly reduced. The effects are twice as strong for concrete with w/c-ratio 0.62 as for concrete with w/c-ratio 0.54.

Interaction between frost action and leaching is a good example of synergy since they together produce an amount of damage greater than the sum of their individual effects. However, the effects of abrasion on the scaling resistance are not that strong. But when the concrete surface has been weakened by leaching and frost action, the effects of abrasion are suddenly greater. This is another example of synergy. When the weakened and/or damaged concrete surface layer is removed due to abrasion, the process starts all over again.

The scaling resistance in the presence of de-ionized water is *Very good* for the concrete mixes with w/c-ratio 0.54 and 0.62, whereas leaching significantly reduces the scaling resistance of the same mixes. Since the ion concentration of the water in Swedish rivers is low and the water can be slightly acidic, leaching of the concrete surface is a continuous process. Thus, the scaling resistance of concrete in winter is reduced. This reduction in the scaling resistance may explain the damage to the concrete surface at the waterline of hydraulic structures.

Since similar damage to the concrete surface can be observed on the upstream and downstream side of hydro power dams, the effects of abrasion by ice floes are of secondary importance compared with the effects of leaching. On the downstream side of a dam, the water flows away from the dam and carries away the ice floes. Consequently, damage to the concrete surface on the downstream side would be rare to see if the effects of ice abrasion were of superior importance.

According to the results obtained in this study, leaching of the concrete surface significantly reduce the scaling resistance of concrete. The effects of leaching during the snowmelt runoff period, frost action in winter and ice abrasion in spring recur every year. Hence, progressive damage to the concrete surface at the waterline of hydraulic structures is caused by interaction between leaching, frost action and abrasion. However, the scaling resistance of concrete is increased with decreasing w/c-ratio.

6 Macroscopic Ice Lens Growth in Hardened Concrete

As shown in Section 3.2, spalling of concrete has been observed below the water level on the upstream face of some buttress and arch dams without heat insulating walls on the downstream side. Pieces of concrete have fallen off the dams. Based on the work by Collins (1944) and field observations by Rogers and Chojnacki (1987), it was suspected (but neither proved nor investigated) that internal damage may occur due to macroscopic ice lens growth in water retaining concrete structures, such as thin concrete dams and concrete water tanks.

During the winter, the water temperature on the upstream side of a dam is slightly above the freezing point of water, whereas the air temperature is below freezing. In general terms, one can say that the dam is subjected to unidirectional freezing, which means in this case that only the downstream face is subjected to freezing. In this study, unidirectional freezing is mostly termed freezing.

During the period when the dam is subjected to 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 moisture content of concrete may be high, the risk of frost damage and/or subsequent growth of macroscopic ice lenses are imminent.

In this study, conditions for macroscopic ice lens growth in hardened concrete subjected to unidirectional freezing have been studied in the laboratory. The top surface of concrete specimens of size 150x150x70 mm was subjected to freezing, whereas the bottom surface was in contact with unfrozen water. To ensure one dimensional heat flow in the specimens, the remaining surfaces were insulated. The test setup used in this study is shown in (Figure 6-2).

Eight concrete mixes with w/c-ratio between 0.5 and 1.4 were produced and three types of specimens were prepared; (1) specimens kept dry prior to freezing, (2) specimens saturated, subjected to freezing and then dried prior to freezing, and finally (3) specimens, with sheets of paper cast into the concrete, kept dry prior to freezing. The paper layers represent cavities or other imperfections in the concrete.

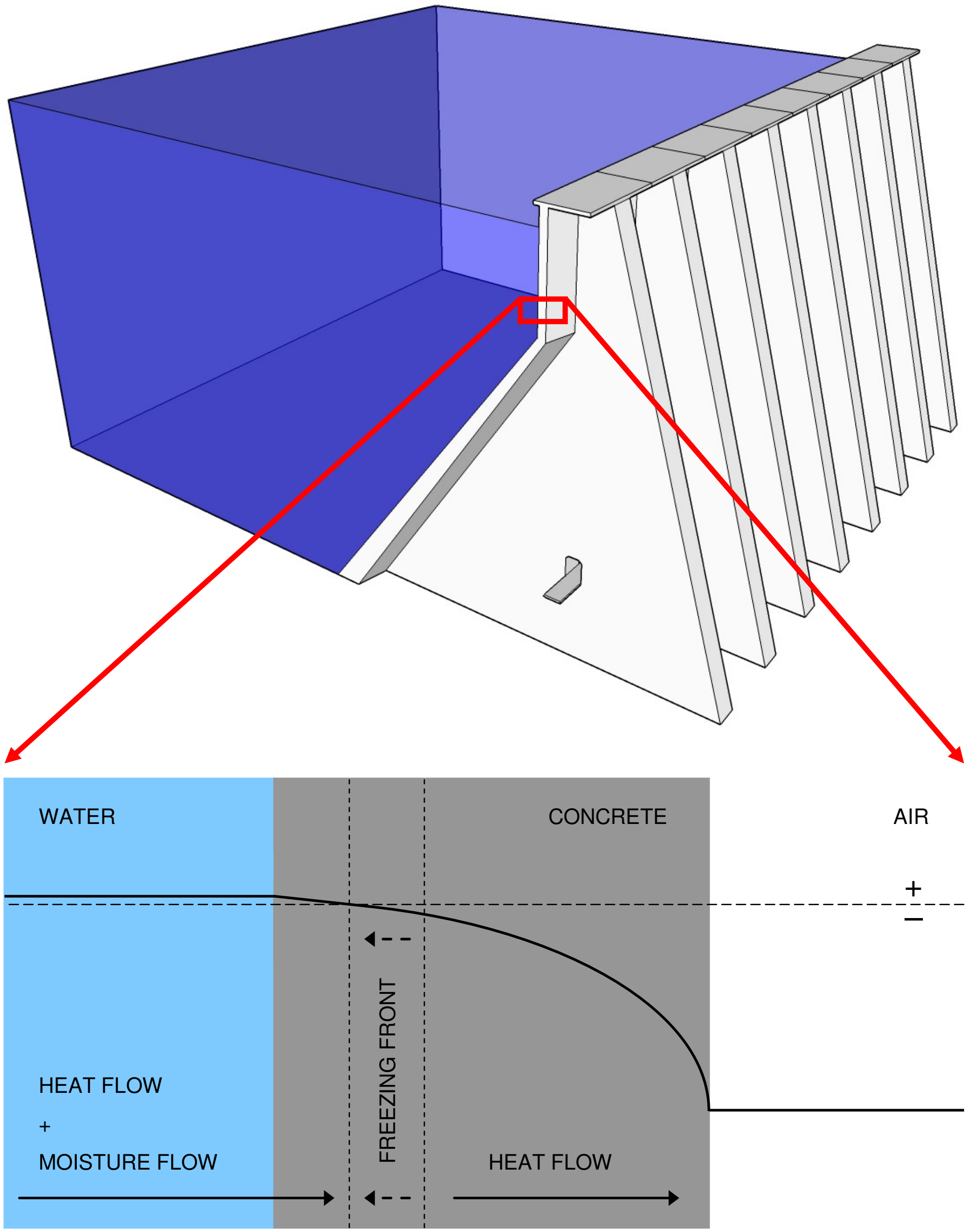

Figure 6-1. Cross-section of a flat slab in winter. Water temperature is slightly above freezing, whereas air temperature is below freezing. A freezing front moves towards the upstream side when heat is conducted towards the cold side, i.e. the downstream side. The risk of concrete spalling due to macroscopic ice lens growth is increased if balance between heat supply and heat loss is reached close to the upstream face where water supply is endless.

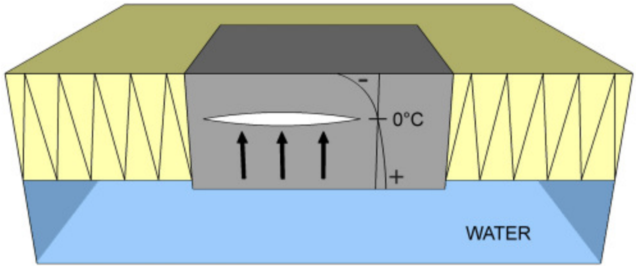

Figure 6-2. Test setup used to subject concrete specimens to freezing.

According to the results obtained in this study, it was shown that macroscopic ice lens growth may occur in undamaged concrete subjected to unidirectional freezing if the w/c-ratio exceeds 0.8. Further, growth of macroscopic ice lenses in concrete damaged by frost action occurs within a few days regardless of the w/c-ratio of the concrete. Also in locations with cavities or other imperfections in the concrete, such as insufficient bond strength between concrete overlay and substrate, there is a risk of concrete spalling due to growth of macroscopic ice lenses. A macroscopic ice lens formed in a specimen with sheets of paper cast into the concrete is shown in Figure 6-3.

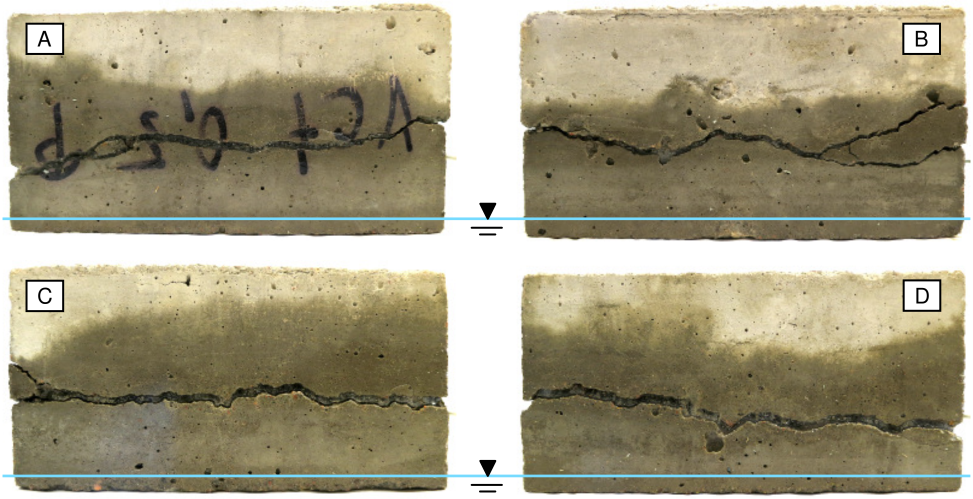

Figure 6-3. Ice lens visible in a specimen with sheets of paper cast into the concrete. All four sides of the specimen with w/c-ratio 0.5 are shown (A-D). The top surface of the specimen was subjected to freezing, while the bottom surface was in contact with unfrozen water.

The susceptibility to macroscopic ice lens growth depends partly on the duration of the freezing period and partly on the w/c-ratio of the concrete. The lower the w/c-ratio the longer is the time of freezing required to form macroscopic ice lenses.

The experimental work performed in this study is fully presented in Paper II.

The risk of concrete spalling on the upstream face of thin concrete dams increases if the moisture content of the concrete exceeds the critical degree of saturation (S_{cr}). When concrete has been damaged by frost action, accelerated deterioration due to macroscopic ice lens growth occurs if the concrete is in contact with water and subjected to long periods of freezing temperatures.

Consequently, the risk of concrete spalling depends partly on the rate of moisture absorption and partly on the frost resistance of concrete. Until the point when the critical degree of saturation (S_{cr}) is reached, concrete dams are not severely damaged by frost action. However, as soon as the critical degree of saturation (S_{cr}) is reached and the dam is subjected to long periods of freezing temperatures, the risk of accelerated deterioration due to macroscopic ice lens growth is imminent.

However, concrete with w/c-ratio less than 0.6 has normally been used in concrete structures subjected to hydrostatic pressure since the 1930s. According to the results obtained in this study, there is no risk of concrete spalling in concrete with w/c-ratio less than 0.9 unless the critical degree of saturation (S_{cr}) has been reached or cavities or other imperfections exist in the concrete.

Unfortunately, spalling of concrete on the upstream face of concrete dams can be difficult to discover from the dam's crest. Inspections by divers or unmanned underwater vehicles are recommended. Providing thin concrete dams with heat insulating walls on the downstream side reduces the risk of damage due to growth of macroscopic ice lenses.

7 Moisture Absorption of Concrete Submerged in Water

The study of moisture absorption of concrete submerged in water is ongoing and no data on the moisture absorption is yet available for presentation. However, the work conducted so far will be presented briefly in this chapter.

According to Fagerlund (2006), entrapped air in compaction voids and air voids is dissolved in water when concrete absorbs water in the over-capillary range. Over the years, the frost resistance of concrete can be reduced when empty spaces where ice can form gradually fill with water. Therefore, it is of the greatest interest to determine the diffusion rate of air in air entrained concrete submerged in water at different depths.

In order to study the moisture absorption of concrete, six concrete mixes were designed with a w/c-ratio between 0.45 and 0.70. The desired air content of 5.0% would require the use of air entraining agents to create air voids in the concrete. The proportions of the mixes are presented in Table 7-1.

Table 7-1. Proportions of the concrete mixes.

w/c	**Cement** [kg/m³]	**0–1 mm** [kg/m³]	**0–8 mm** [kg/m³]	**8-16 mm** [kg/m³]	**Air Content** [%]
0.45	365	319	566	886	5.0
0.50	324	325	580	906	5.0
0.55	291	330	592	923	5.0
0.60	267	334	598	933	5.0
0.65	246	337	604	942	5.0
0.70	229	340	608	949	5.0

To minimize the effects of aggregate occupying too much of the cross-section area in the specimens, all aggregate larger than 8 mm in size was removed from the mixes. Thus, the cement content, remaining aggregate content and air content were proportionally increased. The proportions of the micro-concrete mixes together with a reference mix with w/c-ratio 0.60 are presented in Table 7-2. A CEM I Portland cement (Anläggningscement) was used. The fresh and hardened properties, such as the air content, slump, porosity and compressive strength after 28 days are presented in Table 7-3.

Table 7-2. Proportions of the micro-concrete mixes, including the reference mix.

w/c	Cement [kg/m³]	0–1 mm [kg/m³]	1–4 mm [kg/m³]	0–8 mm [kg/m³]	4-8 mm [kg/m³]	8-16 mm [kg/m³]
0.45	548	479	-	850	-	-
0.50	492	494	-	881	-	-
0.55	446	506	-	908	-	-
0.60	412	515	-	923	-	-
0.65	382	523	-	937	-	-
0.70	357	530	-	947	-	-
0.60R	325	329	65	443	102	829

Table 7-3. Fresh and hardened properties of the micro-concrete mixes, including the reference mix.

w/c	Air Content [%]	Slump [mm]	Strength 28 D [MPa]	Porosity [-]	S at S_{cap} [-]
0.45	7.6	55	50.1	0.24	0.72
0.50	8.1	70	42.0	0.25	0.71
0.55	7.8	45	44.5	0.24	0.72
0.60	8.0	75	38.2	0.25	0.69
0.65	7.7	65	34.4	0.25	0.68
0.70	7.8	65	30.6	0.25	0.68
0.60R	4.3	50	-	0.17	0.80

Concrete cores with the diameter of 95 mm were drilled out from standard cubes in order to avoid unfavourable effects of bleeding on the surfaces. The concrete cores were sliced into discs with an approximate thickness of 10 mm. To study the effects of the hydrostatic pressure on the moisture absorption of air entrained concrete, the specimens were submerged at the water depths 0, 10, 20 and 30 m.

Since the upstream face of arch dams is vertical, the arch dam at Vargfors power plant was chosen as the place to subject the specimens to hydrostatic pressure at the depths of 10, 20 and 30 m. The specimens were placed in baskets attached to wires hanging from the dam's crest. To protect the wires from the action of ice in winter, stainless steel profiles (2+2 m) were mounted on the upstream face of the dam in October 2011 (Figure 7-1). The wires run behind the steel profiles.

Figure 7-1. Stainless steel profiles (A) to be mounted by divers (B) on the upstream face of the arch dam (D) at Vargfors power plant. The top 0.5 m of the steel profiles are above the maximum water line (C).

Since the mounted steel profiles were not damaged by ice action during the winter 2011/2012, the specimens were submerged in June 2012 at the water depths of 10, 20 and 30 m (Figure 7-2). The specimens subjected to hydrostatic pressure at the depth of 0 m (atmospheric pressure) are placed in baskets stored in the laboratory.

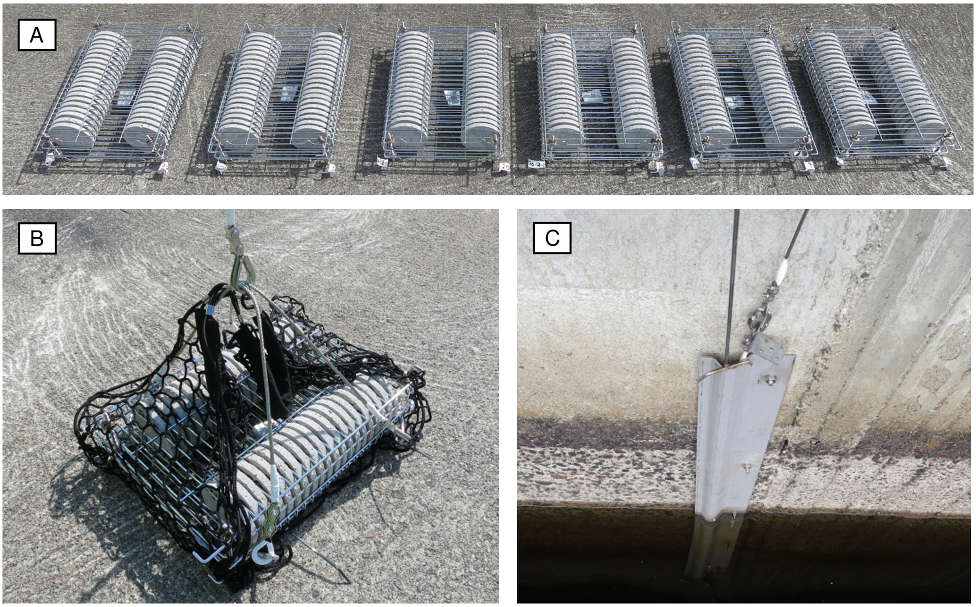

Figure 7-2. The specimens in baskets before submerging at the depths of 10, 20 and 30 m (A and B). Basket submerged with the wire running behind the steel profile (C).

To obtain and maintain steady state conditions for the specimens submerged in water at different depths, measurements will only be performed once a year. All specimens will be brought up to the surface and weighed. Some specimens of each concrete mix will also be brought to the laboratory for determination of the degree of saturation. The results will be used in future research in order to try to determine the diffusion rate of air out of the air voids and eventually out of the material.

8 Discussion

The three questions stated in Section 1.2 will be discussed in this Chapter.

The first question was:

- Which deterioration processes cause progressive damage to the concrete surface at the waterline of hydraulic structures?

According to the results obtained in the experimental studies, the answer to the question is interaction between leaching, frost action and abrasion.

The scaling resistance of concrete in the presence of de-ionized water was *Very good* for the specimens with w/c-ratio 0.54, 0.62 and 0.70 according to the test method SS 13 72 44. However, minor damage to the concrete surface was observed when the frost resistance of the same concrete mixes (except for specimens with w/c-ratio 0.54) was assessed according to the laboratory test method presented in Paper I. The test method was developed to correspond to prevailing climatic conditions at the waterline of hydraulic structures. The results indicate that the effects of frost action on the deterioration of the concrete surface are not strong enough to cause the amount of damage observed at the waterline of hydraulic structures in reality, see Section 3.1.

When the concrete surface was subjected to leaching in water at pH 4 and pH 7, the scaling resistance was reduced according to the test method SS 13 72 44. The reduction was greater for the specimens subjected to leaching in water at pH 4 than in water at pH 7. The reason was that the dissolution of calcium in water at pH 4 was twice as big as in water at pH 7. The amount of loose materials collected from the concrete surface was further increased when the surface was brushed with a steel brush after the freeze-thaw cycles.

Since the normal pH values in Swedish lakes and rivers vary in the range 6 to 8, leaching of calcium from the concrete surface is a continuous process. However, the leaching rate may increase during the snowmelt runoff period when the snowmelt water temporarily lowers the ion concentration of the river water. The concrete surface is thus more susceptible to frost action. During the following winter, the surface layer is damaged by frost action and the damaged concrete may be removed in spring due to ice abrasion. Hence, a new concrete surface is subjected to leaching and the process starts all over again. This recurring process causes progressive damage to the concrete surface.

To sum up, the scaling resistance of concrete subjected to leaching and abrasion is greater for concrete with w/c-ratio 0.54 than for concrete with w/c-ratio 0.62. The use of concrete with low w/c-ratio increases the resistance of the concrete surface to leaching. Hence, the overall resistance to progressive damage to the concrete surface due to interaction between leaching, frost action and abrasion increases.

The second question was:

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

According to the results obtained in the experiments, low quality concrete and/or concrete with internal damage or various types of imperfections are susceptible to macroscopic ice lens growth.

Growth of macroscopic ice lenses was observed only in concrete specimens with w/c-ratio exceeding 0.8, unless the specimens were weakened by frost damage or sheets of paper cast into the concrete. Since the water supply was endless in the test setup, only interaction between the permeability and tensile strength of the concrete could prevent macroscopic ice lens growth.

However, internal damage of concrete due to frost action significantly reduced the resistance to growth of macroscopic ice lenses. Regardless of the w/c-ratio, ice lenses were visible in specimens with internal damage after a few days of freezing. Internal damage of concrete due to frost action increases the permeability and reduces the tensile strength of concrete. Consequently, the risk of macroscopic ice lens growth is enhanced during the next period of freezing.

Growth of macroscopic ice lenses was observed also in specimens with sheets of paper cast into the concrete. However, the time until failure of the specimens was dependent on the w/c-ratio. The lower the w/c-ratio, the longer is the time of freezing required to form macroscopic ice lenses. Hence, reduced permeability of concrete due to lower w/c-ratio reduces moisture transport to growing ice lenses.

In hydro power dams and other types of retaining concrete structures subjected to hydrostatic pressure, concrete with w/c-ratio less than 0.6 has normally been used since the 1930s. The results obtained in this study indicate that there is no risk of concrete spalling due to macroscopic ice lens growth in undamaged concrete with w/c-ratio less than 0.9.

However, internal damage may occur if the moisture content of concrete exceeds the critical degree of saturation (S_{cr}) and the structure is subjected to long periods of freezing temperatures. Hence, next time the structure is subjected to freezing, the risk of accelerated deterioration due to growth of macroscopic ice lenses is increased. This course of events may explain the examples of concrete spalling on the upstream face of the concrete dams presented in Section 3.2.

To sum up, mostly low quality concrete and/or concrete with internal damage or various types of imperfections are susceptible to growth of macroscopic ice lenses. Also high quality concrete can be susceptible to macroscopic ice lens growth if the critical degree of saturation (S_{cr}) is reached. Hence, the risk of concrete spalling on the upstream face of thin concrete dams is dependent on the degree of saturation, which in turn is dependent on the rate of moisture absorption of concrete.

The third question was:

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

This question cannot be answered yet. It may be possible to answer the question when the experiments are completed. The experiments will perhaps show that entrapped air in compaction voids and air voids can be dissolved in water and that the air voids are filled with water over time. If that is the case, the frost resistance of concrete is reduced. The results can perhaps also be used to estimate the rate of moisture absorption of concrete and to predict the susceptibility to frost action of air entrained concrete in hydraulic structures.

Final remarks:

The basis for the present study is observations of concrete damage in hydro power structures in Sweden. The experimental work has focused on the effects of frost action on the deterioration of concrete in hydro power structures. However, the results obtained may also be applicable to concrete structures in harbours, canals and bridge foundations, since the exposure conditions, in many cases, are similar.

9 Conclusions

According to the experimental work performed within this licentiate thesis, the following conclusions can be drawn:

- The scaling resistance of concrete with w/c-ratio 0.54, 0.62 and 0.70 in the presence of de-ionized water is classified as *Very good* according to the test method SS 13 44 72.

- Progressive damage to the concrete surface at the waterline of hydraulic structures is caused by interaction between leaching, frost action and abrasion.

- Leaching of calcium from the concrete surface is a continuous process and it significantly reduces the scaling resistance of concrete with w/c-ratio 0.54 and 0.62 in the presence of de-ionized water.

- The resistance to progressive damage caused by interaction of multiple damage mechanisms, such as leaching, frost action and abrasion, is increased in concrete with decreasing w/c-ratio.

- Growth of macroscopic ice lenses may occur in low quality concrete and/or concrete with internal damage or various types of imperfections.

- Macroscopic ice lens growth may occur in undamaged concrete with w/c-ratio exceeding 0.8.

- Regardless of the w/c-ratio, internal damage of concrete due to frost action significantly reduces the resistance to growth of macroscopic ice lenses.

- The risk of concrete spalling on the upstream face of thin concrete dams is dependent on the degree of saturation, which in turn is dependent on the rate of moisture absorption of concrete.

10 Future Research

The following proposals for future research are partly based on the experimental work performed in this study and partly based on the needs of owners of hydraulic structures to be able to predict the service life of their structures.

Proposal 1:

It was shown that leaching of calcium from the concrete surface leads to reduced scaling resistance of concrete. The relationship between leaching of calcium and the reduction of scaling resistance is, however, not known. If this relationship is determined, a model can be developed to predict the rate of deterioration of the concrete surface at the waterline of hydraulic structures.

Proposal 2:

Damaged concrete in hydraulic structures can be repaired with concrete overlays. An overlay may influence the moisture conditions in the substrate. What impact it will have on the frost resistance of the substrate, interfacial zone and overlay is not known. Field measurements and laboratory tests will be undertaken in order to throw light upon this question.

Proposal 3:

The risk of internal damage due to frost action in concrete structures submerged, or partially submerged, in water is partly dependent on the moisture content of concrete. Hence, a model for moisture absorption at high moisture contents with regard to diffusion of entrapped air will be developed. The model will be verified by means of experiments presented in Chapter 7. The model can be used to predict the time until the critical degree of saturation (S_{cr}) is reached in concrete submerged in water.

Proposal 4:

A model for macroscopic ice lens growth in hardened concrete can be used to further study the risk of concrete spalling on the upstream face of thin concrete dams and other water retaining structures subjected to long periods of freezing temperatures.

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