REHABILITATION AND PREVENTION OF FROST DAMAGE TO THIN CONCRETE DAMS IN COLD REGIONS

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ABSTRACT

The Storfinnforsen and Ramsele buttress dams were built in the 1950s as two of the largest concrete dams in Sweden, almost 40 m high and 2000 m long in total. Both dams were rehabilitated in the 1990s since cracking of the water retaining flat slab had caused water leakage and frost damage to the downstream face in the vicinity of cracks and joints. During underwater inspections, frost damage was also discovered on the upstream face between the normal water level and some 10–12 m down. Large pieces of concrete up to 10 m2 in size and 200 mm in thickness were missing and exposing the reinforcing steel to river water. Formation of ice coatings on the upstream face in winter was confirmed by both divers and temperature measurements. None of the dams had been provided with heat insulating walls on the downstream side to protect the concrete from freezing in winter.

Our field and laboratory investigations show that thin concrete dams can undergo rapid deterioration in cold regions which may threaten the structural integrity of the dams. This paper presents a theory to explain the causes of frost damage to the upstream face of the buttress dams as well as the experimental work that was conducted to verify the theory. A new test method was developed in order to determine the risk of frost damage in hardened concrete in contact with water and subjected to unidirectional freezing.

Also the effects of water leakage through cracks and joints are discussed with regard to the durability of the dams. In addition to the risk of frost damage, water leakage causes leaching of lime and thus locally increasing the porosity and reducing the mechanical strength of concrete. Leaching may also increase the risk of reinforcement corrosion due the decrease in pH value. Furthermore, this paper describes the rehabilitation works carried out in the 1990s and how they have performed. A discussion is also given on the importance to carefully analyze the structural behavior of dams before initiating rehabilitation works to prevent further deterioration and thus extend their useful service life.

1. INTRODUCTION

Two of the largest concrete dams in Sweden, the buttress dams at Storfinnforsen and Ramsele, were built by Krångede AB (today part of Uniper) between 1949 and 1958. Both dams are situated along the river Faxälven in northern Sweden. The Storfinnforsen hydro power plant was completed in 1954. The dam is 40 m high and 1200 m long, including an 800 m long concrete dam (Figure 1A). Construction of the Ramsele hydro power plant began after completion of the Storfinnforsen project. The buttress dam at Ramsele was completed in 1958, reaching 400 m in length and 35 m in height (Figure 1B). In both dams, the flat slab is 1.2 m thick at the top and as much as 2.6 m thick at the base. None of the dams was provided with heat insulating walls on the downstream side when constructed.

Figure 1 : The concrete buttress dams at Storfinnforsen (A) and Ramsele (B).

In spite of similar structural design, the composition of the concrete material differs between the two dams. During the construction of the buttress dam at Storfinnforsen, a standard Portland cement was used as binder. According to the guidelines of that time, the cement content of concrete in hydraulic structures was allowed to vary between 310 and 350 kg/m3 depending on the maximum aggregate size. The water to cement-ratio (w/c-ratio) was about 0.5. An air entraining agent was added to the fresh concrete mix in order to improve the frost resistance. The effects of air entrainment had been discovered only a few years earlier. However, due to lack of experience and uncertainties about the stability of entrained air voids, the concrete was hand tamped.

The type of cement prescribed by the guidelines for design and construction of hydraulic structures was changed before the construction of the buttress dam at Ramsele had begun. To reduce the risk of cracking due to the evolution of heat during the hardening process of concrete, a low heat Portland cement was used instead of a standard Portland cement. The cement content and the w/c-ratio were unchanged, whereas the concrete was vibrated instead of hand tamped during casting.

A few years after commissioning of the two dams, respectively, cracking was observed in the flat slab. The cracking resulted in water leakage and subsequent frost damage to the downstream face. Frost damage was also discovered on the upstream face between the lowest water level and some 10 m down. In the following sections, the operational history of the dams, including field and laboratory investigations on the concrete deterioration processes, are presented. Also the rehabilitation works carried out on the two dams and their performance are briefly discussed.

2. OPERATIONAL HISTORY OF THE DAMS

2.1 Exposure conditions at the dam site

The climate in Sweden varies greatly over the year. Summers are warm and winters are cold. In the northern parts of Sweden, the monthly average temperatures varies between -14 in winter and +12 °C in summer (Nevander & Elmarsson 2006). Air temperatures can drop to -30 °C during the winter and reach over +30 °C in the summer. Hence, the difference between daily minimum temperatures in winter and daily maximum temperatures in summer is normally in the range of 50 to 60 °C.

2.2 Cracking of the flat slab

Shortly after the completion of the buttress dam at Storfinnforsen, a considerable amount of cracks appeared in the flat slab. The cracking was mainly horizontal and it became worse during the initial reservoir filling (Figure 2A). Investigations conducted in the early 1960s showed that the cracks were continuous from one side of the flat slab to the other. Most of the cracks developed at depths greater than 10 m where the flat slab continuously becomes thicker (Bergström & Nilsson 1962). A second crack mapping was conducted in the late 1980s. It showed that the number of cracks had increased.

Also in the case of the buttress dam at Ramsele, cracks developed in the lower part of the flat slab after completion. However, the amount of cracks was significantly smaller in comparison with the dam at Storfinnforsen (Fahlén & Näslund 1991). Since the structural design of the dams is similar, the choices of cement type and compaction method are major differences that may have contributed to the greater number of cracks developed in the Storfinnforsen dam. The standard Portland cement produces a greater amount of heat during hardening compared to the low heat Portland cement. The greater the amount of heat generated, the higher is the risk is of cracking due to contraction of the hardened concrete during cooling. Further, hand tamping increases the risk of inadequate compaction of concrete. Cracking of concrete in water retaining structures is generally associated with water leakage, leaching and subsequent repair works.

2.3 Leaching of concrete

The amount of dissolved minerals in Swedish river waters is generally low in comparison with most other rivers around the world. The reason is partly due to the bedrock geology of Sweden and partly due to the fact that snowmelt runoff water usually contains very small amounts of dissolved minerals. Therefore, most Swedish river waters can be classified as soft water.

When soft water flows through cracks in concrete, two mechanisms occur; dissolution of solid phases and transport of dissolved ions out of the concrete. Dissolution of solid phases is caused by hydrolysis in order to maintain thermodynamic equilibrium between the pore solution of concrete and the surrounding hydration products. Water flowing through cracks brings dissolved ions out of the concrete where efflorescence may form on the surface (Figure 2A).

Calcium hydroxide (CH) and calcium silicate hydrates (C-S-H) are volumetrically the two most important solid phases in hardened Portland cement paste. In a well-developed paste with w/c-ratio 0.5, CH occupies about 15 % and C-S-H about 50 % (Taylor 1997). CH is less stable when in contact with soft water than C-S-H is. Over time, leaching of calcium compounds leads to an increase of porosity, reduced pH value and reduction of strength. Efflorescence (calcium carbonate) on concrete dams is produced due to the reaction between CH and carbon dioxide in the air.

The water leakage through a couple of cracks in the buttress dam at Storfinnforsen was measured over 2-year periods in the early 1960s and late 1980s, respectively. It was noticed that the leakage rate varied seasonally. Maximum leakage rates were present during the winter period while minimum rates occurred during the summer period. In the late 1980s, the water leakage in cracks and dilatation joints gave rise to concerns about the durability and structural integrity of the dams. As mentioned before, leaching of calcium compounds reduces the mechanical strength of concrete. The subsequent decrease in pH value may cause reinforcement corrosion in the long-term perspective. Furthermore, freezing of leakage water in cracks and on the downstream face increases the risk of frost damage.

2.4 Frost damage to concrete

Upon freezing, the volume of water increases by about 9 %. If the water content of concrete exceeds the critical degree of saturation, there is not enough space available for the volume expansion. Hence, frost damage occurs when the internal pressure due to ice formation exceeds the strength of concrete. There are generally two types of frost damage; scaling of the surface but minor losses in strength, and minor or no scaling of the surface but large losses in strength (Powers 1945). The frost resistance of concrete can be improved by the use of air entraining agents that produce proper air void systems. Air voids provide empty spaces within the concrete where ice can form without exerting pressure.

During inspections of the buttress dam at Storfinnforsen, spalling of concrete was observed in the vicinity of leaking cracks and dilatation joints on the downstream face. In some places, the concrete cover was missing. In other places, the concrete appeared soft and could be removed by hand. During inspections of the upper part of the upstream face, divers were able to remove pieces of concrete with their bare hands. The damaged areas varied between 0.5 and 10 m2 in size and were up to 200 mm in depth, leaving reinforcement bars open in the water (Figure 2B). The majority of the damaged areas were located below the normal water level and some 10 m down. Reservoir water level fluctuations are limited to 0.5 m. Hence, frost damage to the upstream face occurred underwater. Similar damage to the upstream face, but to a lesser extent, was discovered on the buttress dam at Ramsele.

Figure 2 : Efflorescence on the downstream face due to leaching (A). Frost damage to the upstream face (B).

2.4.1 *Temperature distribution*

Since none of the dams at Storfinnforsen and Ramsele had been provided with heat insulating walls, the downstream face was subjected to freezing in winter. It was initially believed that the reservoir water provided enough heat to prevent the flat slab from freezing. However, divers reported that up to 300 mm thick ice coatings were formed on the upstream face of the buttress dam at Storfinnforsen in winter. Formation of ice coatings was later confirmed by temperature measurements. At 18 m water depth, the upstream face temperature fell below 0 °C on several occasions (Eriksson 1994).

During the winter when the dams are subjected to unidirectional freezing, heat is conducted from the upstream side towards the downstream side (Figure 3). If the heat loss is greater than the heat supply, a freezing front moves towards the upstream side. Until equilibrium between the heat supply and the heat loss is obtained, the freezing front continues to move towards the upstream side. Ice coatings on the upstream face confirmed that balance in heat transfer was not reached until the freezing front had reached the upstream face.

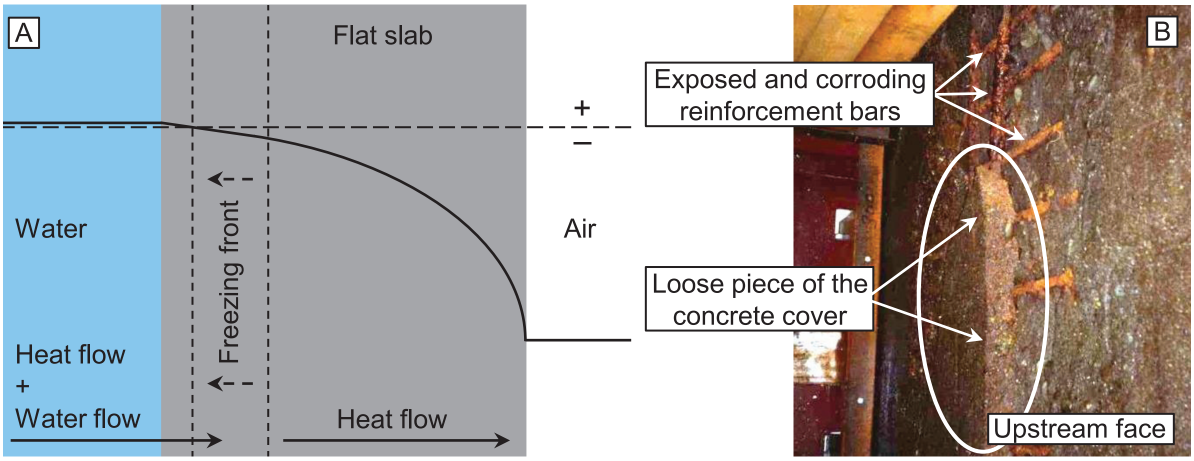

Figure 3 : Movement of the freezing zone within the dam (A). Exposed reinforcement bars due to frost damage to the upstream face of the buttress dam at Storfinnforsen (B).

2.4.2 *Water content*

As mentioned before, water expands about 9% upon freezing. Hence, the frost resistance of concrete depends on the ability to allow ice formation within the material without cracking it. When the water content of concrete exceeds a certain percentage, there is no longer enough space available for the volume expansion of ice. Fortunately, the use of air entraining agents provides empty spaces within the concrete where ice can form without exerting pressure to the surrounding material. However, the behaviour of long-term submersion of air entrained concrete in water is not yet understood.

In the long-term perspective, entrapped air in air voids is likely to slowly dissolve in the water when concrete is submerged (Fagerlund 2006). Hence, the ability of concrete to resist freezing gradually decreases when the air voids fill with water. It is therefore of great importance to monitor the changes in the water content of concrete submerged in water and at risk of freezing in winter.

During November 2013, concrete cores with diameter 74 mm and length 275 mm were drilled out from the upstream face of the buttress dam at Ramsele. The concrete cores were drilled out at 10 and 18 m water depth. When the concrete cores were brought to the surface, they were immediately cut into smaller pieces. The pieces of concrete were weighed before they were sent to the laboratory for determination of the degree of water saturation. The degree of saturation (S) is given in Equation (1):

$$S = \frac{m_{wet} - m_{105}}{m_{sat} - m_{105}} \qquad ...(1)$$

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. The results are shown in Figure 4. As can be seen in the figure, the water content is greater at 18 m water depth compared to 10 m. At both depths, the degree of saturation is close to 1 which is equivalent to water saturation. At such water content levels, there is an imminent risk of frost damage to concrete if subjected to freezing.

Since the buttress dam at Storfinnforsen is four years older than the Ramsele dam, it is assumed that similar results on the degree of saturation are to be expected for the flat slab of the Storfinnforsen dam. However, it cannot be determined when the critical degree of saturation was reached in either of the dams. Considering the damage to the upstream face, it can be concluded that the concrete was susceptible to freezing already during the 1980s. Probably, the critical degree of saturation was reached earlier in the Storfinnforsen dam compared to the Ramsele dam. One reason may be the old method of using hand tamping for compacting the concrete at Storfinnforsen. Another reason may be the lack of experience of using air entraining agents that resulted in low frost resistance.

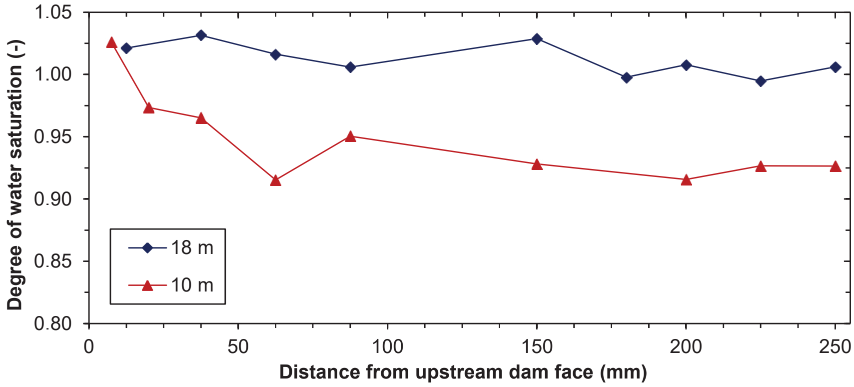

Figure 4 : Degree of water saturation in two concrete cores from the buttress dam at Ramsele.

As shown by the operational history of the two buttress dams at Storfinnforsen and Ramsele, including the measurements on the degree of saturation of concrete, the conditions leading to frost damage were most likely fulfilled in both dams. In the next sections, it will be shown that frost damage can lead to rapid degradation of concrete dams.

3. MACROSCOPIC ICE LENS GROWTH

3.1 Thin concrete dams with severe frost damage

There have been several cases in Sweden where thin concrete dams have sustained severe frost damage. None of the dams had been provided with heat insulating walls to protect the concrete from freezing in winter. In most cases, the damage was repaired when discovered. A common denominator was that frost damage was sustained to both the upstream and downstream face.

In one case, severe spalling of concrete had been noticed on the downstream face during inspections. Reinforcing steel bars were exposed in some places and the concrete surface was visibly wet due to water leakage through cracks in the flat slab just above the damaged areas. However, no measures were taken to prevent further degradation of the dam. Suddenly, a hole appeared in the flat slab in early spring (Figure 5A-C). The size of the hole was approximately 0.8 m in width and 1.2 m in height. All loose pieces of concrete were flushed away by the water escaping through the hole. Reinforcing steel bars were seen from both sides of the flat slab.

The buttress dam was built in the early 1940s, making it about 70 years old when the hole appeared. The maximum height of the dam is 9 m and the crest length is 51 m. 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 authors. Due to the severe damage sustained to the dam, it was temporarily taken out of service.

3.2 Mechanism for severe frost damage

A hypothesis that has been formed over time is that poor quality concrete or the effects of aging make concrete susceptible to growth of macroscopic ice lenses when subjected to long periods of freezing. Formation of macroscopic ice lenses is a well-known phenomenon in soil since it causes frost heave in winter (Taber 1930). In laboratory tests, it was shown that the formation of macroscopic ice lenses occur perpendicular to the heat flow direction (parallel to the ground surface). It was stated that three conditions have to be fulfilled to facilitate frost heave; (1) a frost susceptible soil, (2) a water source and (3) sufficiently low freezing temperatures in the ground. Growth of macroscopic ice lenses continues as long as the heat loss is balanced by the heat supply at the depth of the ice lenses. If the balance is lost, the freezing front moves either downwards or upwards in the ground.

Until now, only a few studies have been conducted on the risk of macroscopic ice lens formation in hardened concrete. In Great Britain, delaminations were observed in concrete pavements during the 1940s (Collins 1944). To determine the cause of damage, a test method was developed where the top of concrete cylinders was exposed to freezing, while the bottom was submerged in heated water. After some time, horizontal cracks appeared about 25 mm below the top of cylinders of very low strength concrete. Unfortunately, the results do not provide a satisfactory explanation to the damage sustained to the upstream face of the buttress dams at Storfinnforsen and Ramsele. The reason is that normal quality concrete with w/c-ratio 0.5 was used during the construction of the dams. On the other hand, the concrete deterioration indicates that the conditions for macroscopic ice lens formation have been fulfilled in the dams at some point of time.

It has already been shown that sufficiently low temperatures were reached to cause freezing of water on the upstream face of the buttress dams at Storfinnforsen and Ramsele. Further, the reservoirs may theoretically provide enough water for ice lens growth within the dams. Also the third condition, stating that the material has to be frost susceptible, has to be fulfilled to facilitate macroscopic ice lens growth. Hence, a new test method was developed in order to determine the risk of formation of macroscopic ice lenses in hardened concrete subjected to unidirectional freezing.

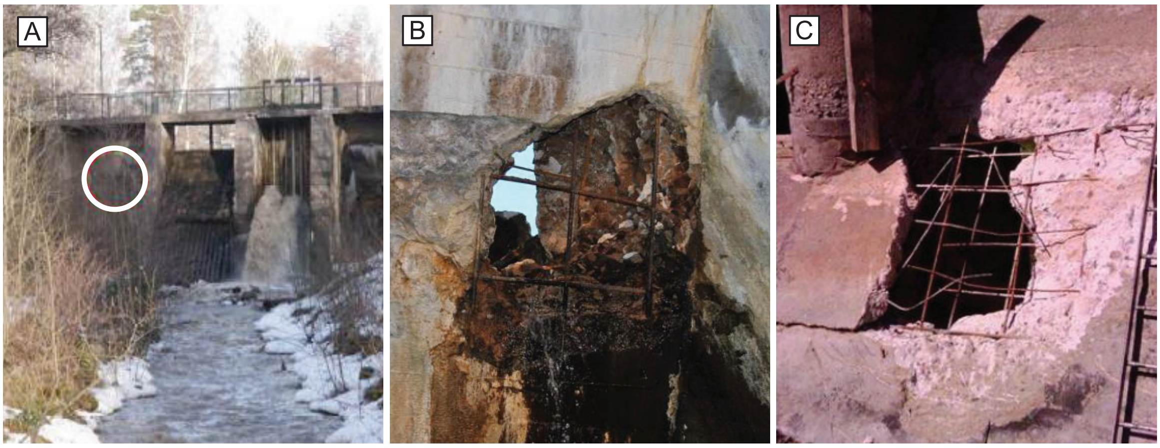

Figure 5 : A 70 year old buttress dam (A). In early spring, a hole appeared in the flat slab at a location where frost damage previously had been noticed on the downstream face (B-C).

3.3 Experimental work

3.3.1 *Test setup*

The risk of macroscopic ice lens growth in hardened concrete subjected to unidirectional freezing was studied in the laboratory. A test setup was designed to correspond to conditions present at the two dams (Figure 6). 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 specimens were placed in a box filled with water, letting the lower surface stay in contact with water. Moreover, a heating coil was placed on the bottom of the box to control even water temperature. Also a water pump was put into the water to keep it circulating.

In order to create the temperature gradient over the specimen, the air temperature was set to -17.5°C and the water temperature to +3°C. Due to temperature fluctuations in the freezer, the air temperature varied between -15 and -18°C. The water temperature varied between +2.5 and +3.5°C.

3.3.2 *Specimens*

Eight concrete mixes were designed with w/c-ratio in the range of 0.5 to 1.4. No air entraining agent was used. Portland cement (42.5 N MH/SR/LA) was used as binder. Concrete mixes with w/c-ratio 0.5 and 0.6 have historically proven suitable for the construction of hydraulic structures in cold regions. Further, the remaining concrete mixes were used to determine the w/c-ratio over which macroscopic ice lens growth may occur. However, concrete mixes with high w/c-ratio can also be considered as concrete subjected to different degrees of leaching due to percolating water.

Three types of specimens were produced; (1) specimens of mechanically sound concrete, (2) specimens with internal damage due to frost action and (3) specimens with sheets of paper cast into the concrete to represent cavities or other imperfections of the concrete. The specimens of mechanically sound concrete were primarily used for reference purposes.

Internal damage due to frost action increases the permeability of concrete and reduces the strength of the material. Hence, the ability of concrete to resist macroscopic ice lens growth may decrease. Based on the measurements of degree of water saturation, including the observations of ice coatings on the upstream face of the buttress dams, it is reasonable to believe that internal damage due to frost action has or will occur over time. Consequently, the risk of macroscopic ice lens growth in concrete with internal damage due to frost action was studied.

The paper sheets cast into the concrete represent a plane of weakness perpendicular to the heat flow direction. This plane of weakness represents various types of imperfections, such as cracks or cavities caused by inadequate compaction of concrete. Especially around the reinforcing steel bars there is a risk of cavities due to difficulties during the compaction of concrete. Hence, the risk of macroscopic ice lens growth in concrete with internal imperfections was studied.

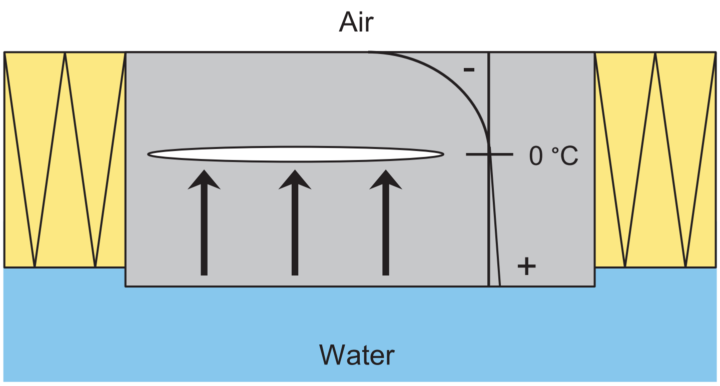

Figure 6 : Test setup used to subject concrete specimens to unidirectional freezing.

3.4 Results and discussion

In rather stable thermal conditions, macroscopic ice lens growth occurred only in mechanically sound concrete with w/c-ratio 0.9 or higher. Such low quality concrete is not normally used in thin concrete dams. On the other hand, if normal quality concrete becomes water saturated and subjected to freezing, internal damage may occur. It was shown that macroscopic ice lenses form in frost-damaged concrete within a few days regardless of the w/c-ratio.

Of similar importance are cavities and other imperfections of the concrete material that may exist in the vicinity of reinforcement bars due to inadequate compaction during casting. It was shown that growth of macroscopic ice lenses also occur in normal quality concrete with imperfections (Figure 7). However, the period of freezing required to facilitate the formation of macroscopic ice lenses increases with decreasing w/c-ratio. Nevertheless, the risk of concrete spalling in thin concrete dams cannot be overlooked since unfavourable temperature and moisture conditions may occur over time in structures with long service life. Hence, extension of the service life of thin concrete dams is closely related to the issue of durability of concrete.

4. REHABILITATION OF THE BUTTRESS DAMS

In spite of several investigations on the crack propagation and how the leaching process deteriorates the concrete in the buttress dams at Storfinnforsen and Ramsele, no major repair or rehabilitation measures were taken until the early 1990s. However, already in 1969, an attempt was made to seal some of the cracks in the Storfinnforsen dam by grouting with epoxy resin. The cracks were sealed, but the water leakage resumed shortly afterwards. Thereafter, no attempts were made to prevent further deterioration of the concrete until the late 1980s when a comprehensive rehabilitation program was launched, including investigations and repairs.

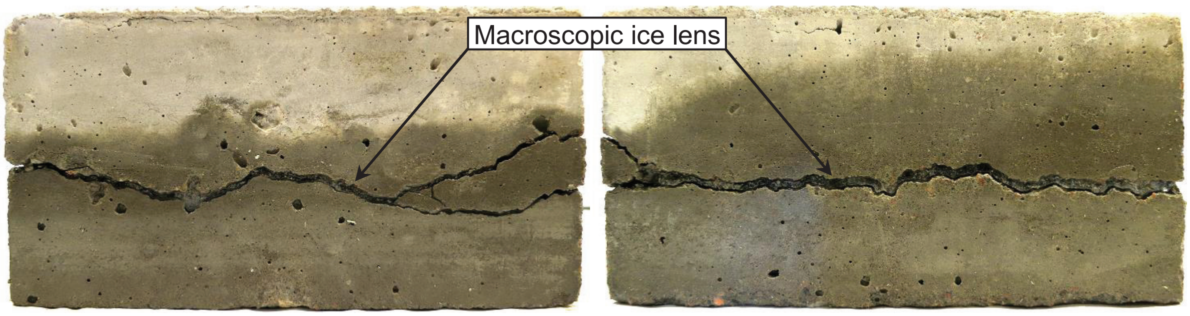

Figure 7 : Macroscopic ice lens formation in a specimen with paper sheets cast into the concrete to represent various types of imperfections of the concrete.

4.1 Rehabilitation works in the 1990s

Based on inspections, investigations and predictions about future deterioration, rehabilitation works of the buttress dams at Storfinnforsen and Ramsele began in 1992 and were completed in 1994. The rehabilitation works involved sealing of cracks in the flat slabs, repairs of frost damage to the upstream and downstream face and the installation of heat insulating walls.

4.1.1 *Repairs to the downstream side*

Water jetting was used to remove degraded concrete from the lower part of the downstream face. In some cases, degraded concrete was removed to a depth of maximum 500 mm. In those cases, 1.4 m long anchor bolts (ø25 mm) were installed to ensure proper bond between the new and old concrete. Only minor repairs to the upper part of the downstream face were conducted.

All surfaces and reinforcement bars were cleaned before they were covered with sprayed concrete. The minimum thickness of the sprayed concrete layer was 60 mm. In cases with insufficient bond between the new and old concrete, a reinforcement mesh was pinned to the old concrete by bolts. Then a second layer of sprayed concrete was applied.

In cracks with major water leakage, temporary drainage by thin plastic tubes was arranged to by-pass the water flow. After completion of the repair works, the tubes were grouted with epoxy resin to stop the leakage. When it was difficult to by-pass the water flow, the cracks were grouted with cement.

4.1.2 *Repairs to the upstream side*

The extent of repairs on the upstream face was smaller compared to the downstream face. A custom-made caisson of steel was manufactured in order to enable repair work below the normal water level on the upper part of the upstream face without lowering the reservoir level (Figure 8). The 10 m high caisson could easily be moved between places where frost damage was discovered.

Figure 8 : The custom-made steel caisson used to allow work on the upstream face of the buttress dams (A). The caisson in place on the upstream side (B).

Degraded concrete was removed by jack hammering and abrasive blasting. Exposed reinforcement bars were cleaned and showed only superficial corrosion. Hence, the reinforcement bars were not replaced. Similar to the downstream face, a layer of sprayed concrete was applied to the old concrete. The repair process is shown in Figure 9.

Figure 9 : Spalling of the concrete cover on the upstream face (A). Degraded concrete removed and reinforcement bars cleaned (B). Sprayed concrete applied (C).

4.1.3 *Installation of heat insulating walls*

Since the rehabilitation works conducted in the 1990s were initiated by concrete deterioration due to cracking, leaching and frost action, it was of great importance to reduce the risk of similar damage in the future. Therefore, the buttress dams at Storfinnforsen and Ramsele were provided with heat insulating walls on the downstream side in order to prevent freezing of the dams in winter. The walls were built between the buttresses, leaving about one third of the buttresses outside the walls (Figure 1A). A controlled warm air flow from the underground power stations was used to heat the air volume between the flat slabs and the heat insulating walls.

4.1.4 *Performance of the rehabilitation works*

About 25 years after the completion of the rehabilitation works, their performance can be evaluated and discussed. It has been noted that the heat insulating walls have prevented further frost damage to the lower part of the downstream face of the dams. Also the upstream face has been protected from further frost damage. However, deterioration of the upper part of the downstream face has continued due to frost action and water leakage through minor cracks. During the winter, the warm air flow has been insufficient to keep the upper part of the dams above freezing.

Since only flat slabs with heavy cracking were rehabilitated, water leakage and subsequent leaching have continued to slowly degrade the concrete in the vicinity of cracks and dilatation joints. In the rehabilitated flat slabs, water leakage stopped in some places, whereas it resumed in other places due to crack propagation through the layer of sprayed concrete. However, the rehabilitation works conducted in the 1990s have reduced the rate of concrete deterioration.

What was not expected after the installation of the heat insulating walls was that additional cracking of the dams would occur. Due to the fact that one third of the buttresses are exposed to outdoor air temperatures and the other two thirds are exposed to the warm air flow from the underground power stations, seasonal temperature variations have caused high tensile stresses in the buttresses (Malm & Ansell 2011). A few years after the installation of the heat insulating walls, inclined cracks were discovered in several buttresses. These cracks have reduced the integrity and the homogeneity of the structures, and thereby endangered the stability of the dams.

4.2 Need for further rehabilitation

Based on further investigations, it was suggested to reinforce the dams by anchor cables to improve the load capacity and to fulfil the stability criteria according to Swedish regulations. This work was completed in 2012. The heat insulating walls will be re-installed further downstream in order to reduce the risk of high tensile stresses in the dams caused by seasonal temperature variations. Efforts will also be made to increase the ability to control the climate in the air volume between the flat slabs and the heat insulating walls. This would also reduce the risk of further frost damage to the upper part of the downstream face of the dams.

5. DISCUSSION

Freezing of concrete in thin concrete dams can lead to severe damage. If no measures are taken to prevent further deterioration, the integrity and the homogeneity of the structures may be reduced over time. Ultimately, the stability of the dams can be endangered. Spalling of concrete may also lead to the appearance of holes and cause water leakage. As shown by the experimental results on the risk of macroscopic ice lens growth, also concrete with low w/c-ratio is susceptible to frost damage given that there are cavities and other imperfections of the concrete material. Such imperfections may exist in the vicinity of reinforcement bars due to insufficient compaction.

The overall decision to initiate rehabilitation of the buttress dams at Storfinnforsen and Ramsele, based on the exposure conditions and the ongoing deterioration processes, was correct. However, the analysis of the effects on the structural behaviour of the dams due to the installation of the heat insulating walls was not comprehensive enough to predict the cracking of the buttresses. Hence, it is of great importance to carefully analyse the structural behaviour of the dams before taking measures to prevent frost damage to thin concrete dams in cold regions.

6. CONCLUSIONS

In this paper, the importance of taking measures to prevent frost damage to thin concrete dams in cold regions has been discussed. It was shown that rapid degradation of concrete may occur when the conditions for macroscopic ice lens growth are fulfilled. Furthermore, rehabilitation of dams with concrete spalling must be conducted in order to maintain the integrity and the homogeneity of the structures. It is therefore important to carefully analyse the effects of any measure to prevent future deterioration due frost action. Otherwise, problems such as endangered dam stability can develop.

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