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Macroscopic ice lens growth: Observations on Swedish concrete dams

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ABSTRACT: The arch dam at Selsforsen and the buttress dam at Storfinnforsen are two concrete dams of which both have suffered from severe surface spalling on the upstream face, far below the full water supply level. A hypothesis is that macroscopic ice lens growth, similar to frost heave in soil, could have occurred within the dam walls. After initial deterioration of the concrete dams by frost damage or cracking, the formation of macroscopic ice lenses could have been made possible. In an attempt to test the hypothesis, specimens of low strength concrete were exposed in the laboratory to climatic boundary conditions similar to those of the dams. After one week of freezing, the upper part of the concrete specimens was separated from the lower part due to cracking. The gradual propagation of the crack, which appeared about 25 mm below the top surface, was caused by macroscopic ice lens growth.

1 INTRODUCTION

1.1 *Background*

Concrete structures, such as hydropower dams, built in the early 20th century, often suffered from severe frost damage when subjected to frequent freezing and thawing during winter time. The findings in the mid 1940s showed that the air content of the concrete was decisive for the durability of structures exposed to freezing and thawing. By adding air entrainment agents (AEA) to the fresh concrete mix, the frost resistance was radically improved in the late 1940s. Frost damage rapidly decreased in concrete structures built after the introduction of AEA.

Surface spalling, similar to frost heave in soil, has nevertheless been observed far below the full water supply level on some Swedish concrete dams. Inspections over time have shown severe spalling of the concrete surface, especially on the upstream face, but also in minor extent on the downstream face. The spalling on the upstream face was sometimes found to be deeper than the thickness of the concrete cover; leaving reinforcement bars open in the water.

1.2 *Selsforsen and Storfinnforsen dams*

The arch dam at Selsforsen and the buttress dam at Storfinnforsen are two dams of which both have suffered from severe surface spalling on upstream and downstream face. None of the dams had been equipped with insulation walls on the downstream side during the construction time. Due to the lack of insulating walls, up to 300 mm thick ice sheets was formed in the winter time on the upstream face, far below the water level. On some occasions, ice was also observed on the downstream face.

The arch dam at Selsforsen is situated along the river Skellefteälv in northern Sweden. The dam was built in the early 1940s and it was initially intended to be replaced by an additional water intake to the power plant, but the plans were never carried out. The arch dam has a crest length of 33 m, a height of 7.6 m and an average thickness of 0.35 m. Standard Portland cement was used with a water/cement ratio (w/c-ratio) of about 0.60. In the late 1960s, the dam had to be repaired since severe damage was found on both upstream and downstream face.

The greater part of the damage to the upstream face was located along two horizontal zones about 1.75 and 5.0 m below the full water supply level (Fig. 1). The width of the damaged zones varied between 0.5 and 2.0 m. During inspections, divers could remove concrete with their bare hands up to a depth of 150 mm. Similar damage was also found on the downstream face. When repairing the arch dam, no attempts were made to restore the damage to the upstream face. The first step in the rehabilitation process was instead to restore the downstream face. The second step involved the casting of a new arch against the existing arch on its downstream side. The new arch was also designed with a thickness of 0.35 m. To prevent further freezing and thawing of the old and new arches, the dam was equipped with an insulating wood panelling on the downstream side.
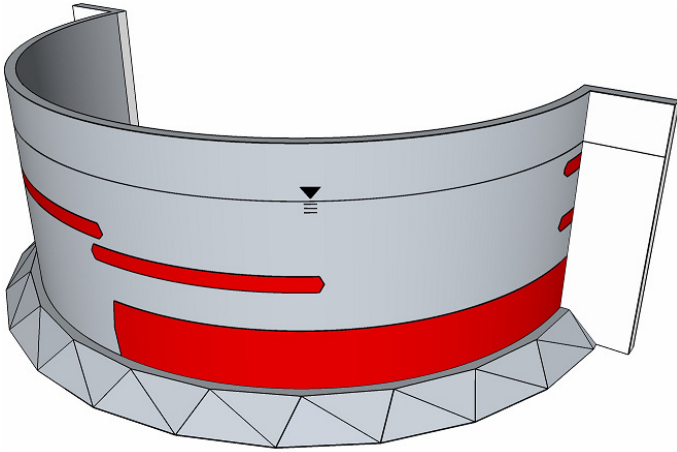
Figure 1. Areas (dark grey) with severe surface spalling on the upstream face of the arch dam at Selsforsen.
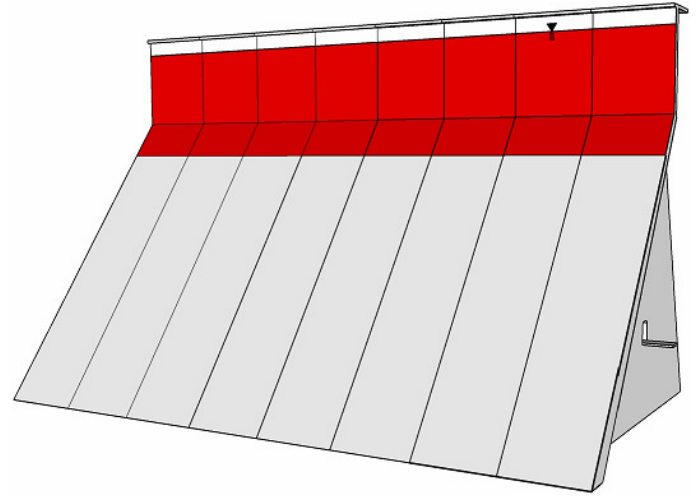

Figure 2. Zone (dark grey) with single areas of surface spalling on the upstream face of the buttress dam at Storfinnforsen.

The buttress dam at Storfinnforsen is situated along the river Faxälven in central Sweden. The buttress dam was built in the early 1950s, the crest length is 640 m and the maximum height is 40 m. The upper part of the deck slab has a thickness of 1.2 m and the lower part 2.6 m. The cement type used in the concrete was Standard Portland cement and the w/c-ratio varied between 0.50 and 0.60. AEA was added when mixing the concrete. However, later measurements have shown an air content less than 3 %, which resulted in an uncertain frost resistance.

Shortly after the commissioning a large number of cracks appeared in the deck slab. The cracking and the following leakage were documented in the early 1960s. The next large investigation took place about 30 years later. Eriksson (1994) could establish the fact that the cracks had increased in number and length. In addition to the cracking in the deck slab, severe surface spalling was found on the upstream face. The major part of the spalling was located between the full water supply level and some 10-12 m down (Fig. 2). The damaged areas varied between 0.5 and 10 m^2 in size and up to 200 mm in depth. On the downstream face, surface spalling concentrated to the vicinity of the dilatation joints was found. In the early 1990s the damage was repaired on upstream and downstream face. The downstream side was also equipped with an insulation wall to prevent further freezing and thawing of the buttress dam during winter time.

1.3 *Working hypothesis*

The aim of this study is to investigate if an already deteriorated concrete also could facilitate the formation of macroscopic ice lenses. If this is the case, it may explain the severe extent of the damage to the upstream faces of the two dams. The study has been performed in a laboratory by exposing concrete specimens of low strength to climatic boundary conditions similar to those of the dams.

2 THEORETICAL CONSIDERATIONS

2.1 *Frost action in concrete*

According to Powers (1945), mature concrete can be deteriorated by only two types of frost damage; scaling and internal frost damage. Scaling will gradually deteriorate the surface of the concrete, while internal frost damage will lower the compressive and tensile strength of the concrete. The two most referred frost mechanisms are the hydraulic pressure theory and the microscopic ice lens growth theory. A third frost mechanism; the macroscopic ice lens growth theory, similar to frost heave in soil, could theoretically cause a complete segregation of the concrete.

In the first theory, the 9 % volume expansion of water when freezing is responsible for exerting pressure on the surrounding cement paste. When the excess water is forced out of the pores, the cement paste will crack if the water pressure exceeds the tensile strength of the cement paste. In the second theory, difference in free energy between water and ice will cause water transport towards the ice lenses inside the pores. Until equilibrium in free energy is obtained, the growing ice lenses will exert an increasing pressure on the surrounding cement paste. The cement paste will crack if the ice pressure exceeds the tensile strength of the cement paste. The third theory, which will be described in a later section, has however never been considered to cause frost damage in mature concrete of normal strength.

A careful design of the air pore system could on the contrary improve the frost resistance considerably. Powers (1949) showed that when adding AEA to the concrete, a lot of small air voids were created. If the small air voids were well distributed in the cement paste matrix, they could give extra space for the ice formation without the water or the ice to exert harmful pressure on the cement paste. The frost resistance of concrete structures was improved.

2.2 Frost heave in soil

When Taber (1930) stated the conditions for ice lens growth in soil, he could thereby explain the noted frost heave in roads and pavements during winter time. In laboratory tests he showed that the formation of macroscopic ice lenses occurred perpendicular to the heat flow direction (Fig. 3). The growth of ice lenses were depending on a continuous water uptake. This was in contrast to the previous theory, where frost heave was explained by the increase in volume of the frozen water in the soil. The growth of macroscopic ice lenses continued as long as the loss of heat from the ice lens towards the soil surface was balanced by the quantity of heat brought up to the ice lens by the water uptake and later set free during phase change. If heat was conducted more rapidly towards the soil surface, the freezing zone moved downwards and the ice lens growth was ceased.

The extent of the frost damage in roads and pavements is primary depending on the frost susceptibility of the soil. According to Hermansson & Guthrie (2005), given a frost susceptible soil and a sufficiently cold environment, the access to water is the most important factor controlling the frost heave. The ground water table height is another factor with a considerable influence on the water uptake ratio. An increased distance between the ice lens and the ground water table results in reduced water uptake and also a subsequently reduced frost heave rate.

Taber (1930) also emphasized the impact of pressure on the ice layer. An increased external pressure on the ice layer required a lower temperature if the macroscopic ice lens growth was to continue. At a certain pressure the ice growth ceased.

Consequently, there are three conditions for macroscopic ice lens growth in a frost susceptible soil:

1) Continuous access to unfrozen water underneath the ice lens.
2) Balance in heat supply and heat loss at the depth of the ice lens.
3) A sufficiently low pressure on the ice lens to allow ice formation.

These conditions might also be fulfilled in concrete.

2.3 Macroscopic ice lens growth in young concrete

A young concrete has properties reminding of the properties in a frost susceptible soil; the permeability is high and the access to water is favourable (Corr et al. 2003). Therefore freezing at early ages of concrete is devastating to its strength and durability. Already in the early 1920s research work was performed in trying to determine the necessary curing time of concrete before freezing.

One of the conditions governing macroscopic ice lens growth in soil is a sufficiently low pressure on the ice lens. When the concrete is cured, the compressive and tensile strengths are increased. When the latter has reached a certain value, the conditions for macroscopic ice lens growth have ceased to exist. An increased tensile strength results in an increased pressure on the growing ice lens, which requires a lower temperature for continued growth. The freeze zone will consequently move gradually downwards.

Fagerlund (1980) has theoretically shown that a tensile strength of the concrete of about 0.1 MPa is sufficient to prevent macroscopic ice lens growth. In addition to the increasing tensile strength, the permeability and the access to water will decrease during the curing time. The necessary time before freezing is rather complex to predict, since it depends on cement type, cement content, admixtures, form-work insulation, temperature conditions, etc. Nowadays, a lot of care is devoted to the curing of concrete before freezing. After form removal, freezing is however no longer considered to endanger the strength of a proper air entrained concrete.

2.4 Macroscopic ice lens growth in mature concrete

Studies performed on the conditions for macroscopic ice lens growth in concrete deal almost solely with freezing of young concrete. Papers or reports on the topic of macroscopic ice lens growth in mature concrete are harder to find. In spite of the fact that some observations have been made, no clear evidence of the existence of macroscopic ice lens growth in mature concrete have yet been found.

Hughes & Anderson (1942) discussed the durability of concrete silo staves in the perspective of acids and frost damage. Severe surface spalling had been observed on both interior and exterior surfaces on a great number of silos. The damage was supposed to have been made possible by the combination of low strength concrete, high capillarity and high moisture content. During cold winter days and nights, the concrete walls froze and ice sheets could be formed against the interior walls.
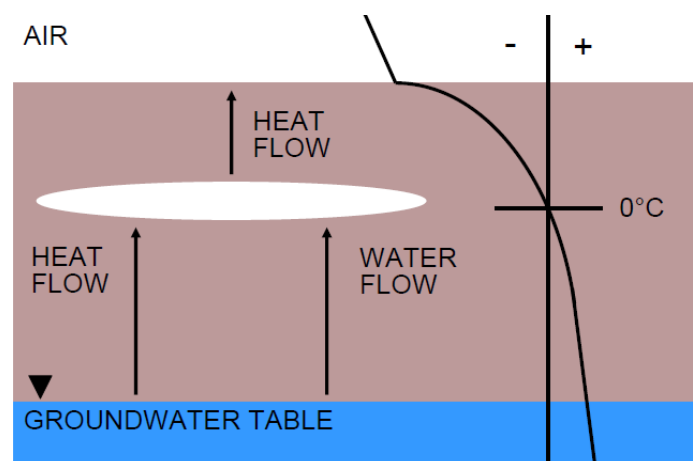

Figure 3. The three conditions for macroscopic ice lens growth in soil are; continuous water uptake, balance in heat flow, and sufficiently low external pressure on the ice lens.

In a study of damaged concrete water tanks in Ontario, Canada, Slater (1985) found freezing of water in structural cracks, in voids around reinforcing steel and within the walls as causes of the damage. The deterioration of the concrete had occurred on both interior and exterior walls, but was more severe and rapid near the bottom of the tanks. This was explained by the increased leakage due to the higher water pressure. Deterioration of large areas up to 10 m^2 of serious spalling was found on some tanks. Temperature gradients of up to 30°C over the concrete walls had been observed.

Rogers & Chonjnacki (1987) investigated the failure of a concrete fish breeding tank in Ontario, Canada. The water in the tank was kept at constant temperature of +4.5°C, while the mean daily air temperature during winter time varied between -10°C and -15°C. The 250 mm thick concrete wall was damaged by cracking and delamination in the centre of the wall. The outer surfaces were generally in good condition. The proposed deterioration mechanism was the macroscopic ice lens growth theory. Water movement towards the outside was triggered by the temperature gradient and resulted in the growth of macroscopic ice lenses in the freezing zone within the wall. The damage had been initiated by the use of low strength concrete.

When Collins (1944) observed delaminations in concrete pavements, he suggested macroscopic ice lens growth as the dominating cause. Collins developed therefore a frost test where cylinders of low strength concrete were exposed to freezing only at the top, while the bottom was submerged in heated water. In very low strength concrete he observed the development of horizontal cracks about 25 mm below the top of the cylinder. Persson & Rosenqvist (2009) made observations of the complete segregation of a specimen half submerged in heated water while freezing. However, no clear evidence on the existence of macroscopic ice lenses was found.

So far, studies have focused on the conditions for macroscopic ice lens growth in young concrete. The conditions for macroscopic ice lens growth in aged or deteriorated concrete are still not fully known. This study will hopefully contribute to increased knowledge about these conditions.

3 METHODS

3.1 Climate at dam sites

In winter time, the air temperature could be -30°C at the two dam sites. It is however not realistic to suppose that the daily mean air temperature is that low. Malm & Ansell (2011) therefore assumed that the winter mean air temperature would be -15°C around the Storfinnforsen dam. The reservoir water temperature was assumed to be +4°C, except for the surface water of +2.5°C. Eriksson (1994) measured the

surface temperature during one winter at 18 m depth on upstream and downstream face. On the upstream face, the temperature fell below -1°C during several weeks, which consequently made the mentioned ice sheets on the upstream face possible.

3.2 Test setup

The test setup was designed to correspond to the conditions present at the two dams; one side of the concrete specimens subjected to freezing temperature and one side in contact with unfrozen water. The effect of water pressure was neglected. To ensure one dimensional heat flow, the specimens were insulated on the remaining surfaces. The specimens were then placed in a box filled with water, letting the lower surface stay in contact with water (Fig. 4).

To be able to control even water temperature, a heating coil was placed on the bottom of the box. The setup was later completed with a pump to keep circulation in the water. The air temperature was set to -20°C and the water temperature to +4°C. Due to temperature fluctuations in the freezer, the air temperature actually varied between -18°C and -21°C.

4 MATERIALS

4.1 Concrete types

Two concrete types of w/c-ratio 1.0 and 0.85 were designed to be used in the study. Since there are few or none evidence of macroscopic ice lens growth in mature concrete, this study should reveal if it is at all possible. For that reason, the w/c-ratios were chosen to represent a high permeable and low strength concrete. The concrete types should also be representative of aged and deteriorated concrete.

The cement type used for the concrete mixes was CEM I Portland cement. No AEA was added in the concrete mix. The proportions of the concrete mixes are presented in Table 1. After initial mixing of cement and aggregates, water was added and the concrete was then mixed for three minutes. The air content was measured to 1.4 % and the slump to 70 mm for w/c-ratio 1.0. Corresponding values for w/c-ratio 0.85 were 3.4 % and 75 mm.
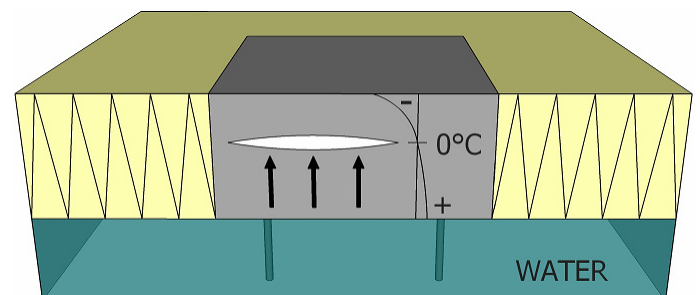

Figure 4. The test setup used for exposing the specimen to an air temperature of -20°C and a water temperature of +4°C.

Table 1. The proportions of the fresh concrete mixes.

w/c	Cement	Sand 0-2 mm	Gravel 0-8 mm	Gravel 8-16 mm
	kg/m^3	kg/m^3	kg/m^3	kg/m^3
1.00	215	173	831	835
0.85	275	208	776	800

4.2 Concrete specimens

Standard cubes, 150x150x150 mm^3, were cast for production of specimens. Since the concrete in the Selsforsen and Storfinnforsen dams had deteriorated, some of the cubes were provided with sheets of copy paper; with the purpose of creating deteriorated concrete inside the cubes. The deterioration, in the form of internal cracks, would perhaps facilitate formation of macroscopic ice lenses. The size of the paper sheets was 130x130 mm^2 and they were placed two and two in horizontal layers, leaving an enclosing boundary of 10 mm of unaffected concrete along the sides of the cubes. Due to the size of the aggregates, the distance between two paper layers was set to 20 mm. This resulted in six paper layers in each cube. The fulfillment of the conditions for macroscopic ice lens growth would then hopefully coincide with one of the paper layers.

Until demoulding, after 24 hours, the top surfaces of the cubes were covered with plastic foil. All of the cubes were then stored in water for 14 days until they were sliced into two specimens of size about 150x150x70 mm^3. The specimens provided with the sheets of paper were also sliced, and each specimen then contained three paper layers (Fig. 5). The specimens were then stored in a climate room with a temperature of +20°C and a relative humidity of about 50 % for another 14 days before the test.

5 RESULTS

After three to four days of freezing, a crack appeared about 25 mm from the top surface of the specimen of w/c-ratio 1.0 (Fig. 6). The crack had propagated around the specimen at the level of the top paper layer. After another three to four days of freezing, the crack had widened to about 1-2 mm. An ice lens had also become visible in the crack. The specimen of w/c-ratio 0.85, provided with paper layers, showed no signs of cracking; neither did the specimens without paper layers.

To verify that the observed cracking was not an isolated case, the test was repeated. After another week of freezing, the same results were observed; cracking of the upper part at the level of the top paper layer in the specimen of w/c-ratio 1.0. No cracks were observed on any of the other specimens. In the future, the experimental work will continue with extended freezing time, different temperatures, etc.
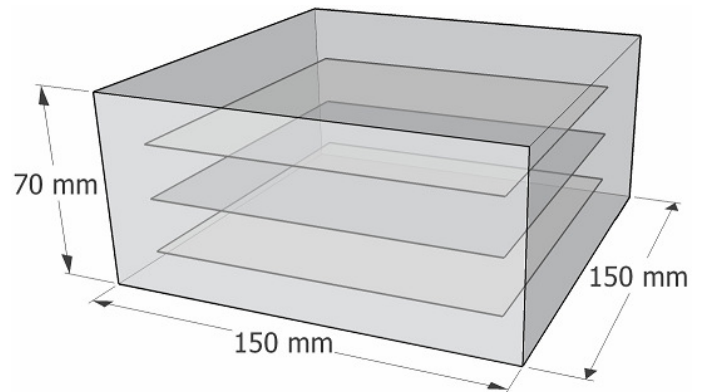

Figure 5. A specimen provided with three paper layers with the purpose of simulating internal cracks within the concrete.

6 DISCUSSION

There might be several potential explanations to the severe extent of the damage to the upstream faces of the Selsforsen and Storfinnforsen dams. Some possible explanations could be that non-frost resistant concrete or concrete of low strength was used in the damaged parts of the dams during the construction time. However, these two explanations could not by themselves explain the extent of the damage. Macroscopic ice lens growth could on the other hand be a plausible explanation to the severe surface spalling.

After one week of freezing, cracks appeared on the specimens of w/c-ratio 1.0, provided with paper layers. The course of events may be described in the following manner – the cooling slowly extended downwards in the specimens and the water in the pores began to freeze. When balance in the heat flow was reached at some level, the loss of heat from the growing ice lenses towards the surfaces was balanced by the quantity of heat brought up by the water uptake and later set free during phase change. Since the specimens were weakened by the paper layers, they could not resist the internal pressure from the growing ice lenses. Consequently, all three conditions for macroscopic ice lens growth were fulfilled.

Figure 6. The crack in the upper part of the specimens of w/c-ratio 1.0 appeared at the level of the top paper layer.

No cracks were observed on the specimens of w/c-ratio 0.85, provided with paper layers. A possible explanation could be that the lower permeability of the concrete required longer freezing time than one week. The lower rate of water uptake might also have slowed down the possible ice lens growth rate. The level of the freezing zone could perhaps be of greater importance than expected. Since none of the specimens without paper layers showed any signs of cracking, the tensile strength of the concrete was sufficient to resist the possible pressure caused by growing ice lenses, at least for one week of freezing. That fact could perhaps explain why the specimens of w/c-ratio 0.85, provided with paper layers, did not fail. If the level of the freezing zone was located between two paper layers, the present conditions would be the same as in the specimens without paper layers. Consequently, the conditions for macroscopic ice lens growth had not been fulfilled.

In concrete dams, built of frost resistant concrete of normal strength, the conditions for macroscopic ice lens growth are likely not to be fulfilled. Even if the water supply in the reservoir is limitless and frequent freezing temperatures occur in winter time, the permeability of the concrete is too low to admit rapid water uptake. The tensile strength of the concrete is also sufficient to resist the possible internal pressure coming from growing ice lenses.

The conditions for macroscopic ice lens growth within concrete dams might however be fulfilled, if the concrete has previously been deteriorated by frost damage or cracking. In this case, water uptake is favourable due to the increased permeability of the concrete and likewise the tensile strength of the concrete is decreased by the deterioration mechanisms. This line of argument is also similar for the specimens of w/c-ratio 1.0, provided with paper layers, where macroscopic ice lens growth was facilitated.

Ice sheets on the upstream face of the dams could theoretically block the water uptake and prevent the fulfilment of the conditions for macroscopic ice lens growth. Nevertheless, the cooling process of massive concrete dams is probably so slow that the freezing time at specific depths in the dam walls could be long enough to facilitate macroscopic ice lens growth. The growing ice lenses will then gradually push the deteriorated concrete towards the upstream face and cause extensive damage over the years. This course of events might be a plausible explanation to why the damage to the upstream faces of the Selsforsen and Storfinnforsen dams became so severe.

7 CONCLUSION

In this study, indications have been obtained that the conditions for macroscopic ice lens growth could be fulfilled in specimens of low strength concrete. The specimens provided with paper layers, with the purpose of creating deteriorated concrete, cracked at the level of the top paper layer. The cracking was caused by macroscopic ice lens growth. The severe damage to the upstream faces of the arch dam at Selsforsen and the buttress dam at Storfinnforsen might have been caused in the same manner.

8 ACKNOWLEDGEMENTS

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