Abstract
Concrete research is focusing ever more on the combined effect of degradation mechanisms on the durability of reinforced concrete structures. While most of the research has been directed at combined carbonation and chloride penetration, recently some attention has been given to emulate combined degradation conditions, especially those existing in Nordic countries (frost attack/chloride penetration), with regards to the harsh environmental conditions. Frost attack of concrete effects the chloride penetration by reducing the concrete cover, and more importantly, by changing the characteristics of the surface and internal concrete due to cracking. Recent research has shown there to be a synergetic effect, but no steps have been taken to characterize and comprehend the mechanisms involved, and to develop a procedure to make it possible to transfer this knowledge to the industry and into practise.

As part of an ongoing research progress addressing this need, series of tests were undertaken to ascertain what influence freeze-thaw cycles would have on the transport of chlorides into concrete. In this paper the, the preliminary result of this research project are presented.

1 INTRODUCTION
In Finland, reinforced concrete structures (RCS) have to perform in rather difficult conditions due to extremely harsh winters, resulting in unique combinations of degradations mechanisms. Traditionally, from a research perspective, freeze-thaw and carbonation have been considered as the predominant degradation mechanisms, with chloride penetration being relegated to a secondary status. However, in light of recent research in Finland [1-3] and internationally, more attention is now being drawn to other degradations mechanism such as chloride penetration and alkali-aggregate reactions and the combination of these with freeze-thaw. Much research has been dedicated to describing the phenomena of freeze-thaw, with
many significant contributions by [4-19]. Despite all the advances in this research, little attention has been given to the interaction between freeze-thaw and chloride ingress. Freeze-thaw reduces the concrete cover due to scaling (in the presence of salts), and by changing the characteristics of both surface and internal concrete due to cracking [17]. As a result, it has been shown [1] that frost attack affects chloride penetration, but research has noted that this phenomenon is not yet understood.

Recent research has shown there to be a synergetic effect between freeze-thaw and chloride penetration, but no steps have been taken to characterize and comprehend the mechanisms involved, and to develop a procedure to make it possible to transfer this knowledge to the industry and into practice [1-3, 19]. For this reason, a research project was undertaken to study the influence that freeze-thaw cycles have on chloride ingress. This paper describes the preliminary result of the ongoing research progress.

2 METHODOLOGY

The purpose of the testing was to ascertain the influence of freeze-thaw cycles on chloride penetration into concrete. For this purpose, two distinct concrete mixes were subject to three different freeze-thaw test cycles and two ponding conditions. In the following the concrete and the test setups are described.

2.1 Concrete mix design and specimen conditioning

Two concrete mixes were prepared with a 0.42 and 0.55 w/b ratios (B42 and B55, respectively). A CEM I 42.5 N-SR3 was used to minimise the possibility of chloride binding. A plasticizer (VB-Parmix) was used in the B42 mix, and an air entrainment agent (Ilma-Parmix) for both mixes. Details of the concrete mixtures and their workability are presented in Table 1, and the characteristics of the air entrainment measured on hardened concrete in Table 2.

Table 1: Concrete compositions and workability

<table>
<thead>
<tr>
<th>Series</th>
<th>w/b</th>
<th>Water (l/m³)</th>
<th>Binder (kg/m³)</th>
<th>Aggregate – Total (kg/m³) &amp; fractions (%)</th>
<th>Slump (mm)</th>
<th>Air (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>&lt;0.125</td>
<td>&lt;0.250</td>
</tr>
<tr>
<td>B42</td>
<td>0.42</td>
<td>175</td>
<td>420</td>
<td>1695</td>
<td>5.8</td>
<td>12.1</td>
</tr>
<tr>
<td>B55</td>
<td>0.55</td>
<td>195</td>
<td>355</td>
<td>1716</td>
<td>4.3</td>
<td>9.7</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of the air pores of hardened concrete.

<table>
<thead>
<tr>
<th>Series</th>
<th>Protective AP 0.02-0.80 mm (%)</th>
<th>Compaction AP &gt; 0.800 mm (%)</th>
<th>Total AP ≈ (%)</th>
<th>Specific surface for protective AP (mm²/mm³)</th>
<th>Spacing factor for protective AP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B42</td>
<td>2.9</td>
<td>1.2</td>
<td>4.1</td>
<td>33</td>
<td>0.21</td>
</tr>
<tr>
<td>B55</td>
<td>5.1</td>
<td>0.8</td>
<td>5.9</td>
<td>21</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The concrete batches were produce in a vertical axis mixer with a 200 litre capacity. Cubic specimens 150 mm in dimension were cast in moulds and compacted using a vibrating table.
24 hours after casting the specimens were removed from the moulds and permanently stored in a climate chamber at RH ≥ 95% at 20 ± 2 ºC until testing. From the results in 2, it can be concluded that very good air entrainment was achieved in both concretes mixes, as shown by the low spacing factor and the specific surface.

Concrete samples were kept in the climate chamber for approximately 8 months to minimise the influence of microstructure changes due to continuous hydration on the test results. After this period, the specimens were stored in a climate chamber at RH ≥ 65% for an additional month. Ten days prior to testing, the concrete specimens were prepared according to the procedure defined in the CEN/TS 12390-9:2006 [20], except with regards to the age of the specimens. A test specimen constitutes a concrete prism with 150x150x50 mm. After a three day period where test specimens were ponded with a layer of deionised water of 3mm, the water was replaced with a 3% by weight of NaCl solution.

2.2 Test setup

Three different freeze-thaw testing cycles were defined to assess influence of freeze-thaw cycles on the transport of chlorides in concrete. These have one day duration, and follow the reference test procedure curve for freeze-thaw scaling, varying only in the minimum temperature reached: -5, -10 and -20°C. The rate of freezing was kept as close as possible to the reference test [20] (see Figure 1).

![Figure 1: Temperature of the solution on the freeze-thaw specimens in the three different freeze-thaw cycles.](image)

The total number of freeze-thaw cycles is 120 for the 1 day test cycle, although currently only the results up to 70 days are available for analysis. The choice of different lower (negative) limit temperature in the cycles, resulting in different durations of time at negative temperatures, was to promote different freezing-thawing behaviour of the brine solution in the pore structure of the concrete. As the temperature decreases, and the longer a certain low temperature is maintained, a greater volume of the pore structure is frozen [3]. In addition, two ponding tests were carried out at +20°C and +5°C, where no freeze-thaw occurs.
During testing, scaled material mass, specimen mass variation and fundamental frequency were measured periodically. In addition, at certain intervals specimens were removed and the chloride profiles determined.

3 RESULTS

3.1 Water uptake

In Figures 2 and 3 the water uptake as a function of time (i.e. freeze-thaw cycles) is presented for concrete B55 and B42, respectively. The water up take values were not adjusted for the weight of scaled material as this was less than 0.7% of the amount of water up taken.

![Figure 2: Water uptake as a function of the number of freeze-thaw cycles for concrete B55.](image)

![Figure 3: Water uptake as a function of the number of freeze-thaw cycles for concrete B42.](image)

The average value of relative dynamic modulus (RDM), measured using fundamental frequency, after 70 freeze-thaw cycles for all three freeze-thaw tests, was 99.5%. These values
indicate that there is practically no internal damage taking place in the concrete. This was expected given the quality of the air entrainment achieved (see Table 2).

Figure 4: Chloride profiles after ponding at +5°C (a) and at +20°C (b).

Figure 5: Chloride profiles after freeze-thaw testing at -5/+20°C (a), -10/+20°C (b), and -20/+20°C (c). Comparison of chloride profiles for B42 after 70 freeze-thaw cycles (d).
3.2 Chloride profiles

In Figures 4 and 5 the chloride profiles are presented for both concretes, and after 28 and 70 cycles (i.e. days), subject to surface ponding and freeze-thaw tests, respectively. Figure 5(d) presents a comparison of chloride profiles for the B42 concrete from different freeze-thaw tests after 70 cycles.

4 ANALYSIS

A theoretical analysis of the test setup identifies as the main transport mechanisms contributing to the ingress of water and chlorides during the course of the test capillary action, diffusion (both water vapour and chloride in the solution) and micro ice lens pumping (as a result of freeze-thaw loading) [3, 14, 17].

4.1 Water uptake

The initial internal moisture condition of the test specimens conditions which transport mechanisms are predominant at any given moment of the test. After a month in which samples were kept at 65% relative humidity, the samples where water ponded for 3 days prior to testing. As a result, a large capillary uptake of water occurs without chlorides. Measurements performed on the same concrete, but at a younger age show that after three days, the B55 concrete had taken up approximately 97% of its capacity due to capillary action, whereas the B42 concrete had taken up approximately 84%. With time, a slight reduction in the volume of water taken up, and an increase in the time necessary for this uptake to occur, is observed. Therefore, at the time of testing, it is can assume that the concrete still has a capacity to up take water due to capillary action, but limited due to the preliminary 3 day ponding with water.

The results for water uptake (see Figures 2 and 3) show that the water uptake is higher for C55 concrete than for C42. This expected based on the characteristic of the concrete composition (i.e. w/b ratio) and the results of capillary uptake.

Samples subject to freeze-thaw cycles show a larger uptake of water when compared to the samples subject only to ponding. This suggests that during freezing, the formation of micro ice lenses might be assisting water uptake. Furthermore, no clear difference is noticed in the uptake of water between the freeze-thaw tests at different temperatures, suggesting that the intensity (i.e. minimum negative temperature) of the freeze-thaw cycle does not have a significant influence on the uptake of water.

4.2 Chloride profiles

Some chloride profiles show a reduction of the concentration near the surface, commonly referred to as the convection zone. These areas were not considered in the analysis.

An analysis of the ponding chloride profiles (Figure 4) reveals the differences expected between a B55 and a B42 concrete, i.e., deeper chloride profile for B55. When looking at the influence of ponding temperature, a clear difference is seen after 70 days, but not at 28 days (see Figure 5(d) for B42 concrete).

The profiles from the different freeze-thaw tests show that the influence of the minimum negative temperature reached during the test is small or negligible. In addition, these profiles also show small or negligible differences when compared to the ponding profiles. This is an unexpected finding as the water uptake in Figures 2 and 3 is clearly larger for the concretes with freeze-thaw cycles than with just ponding. It is thought that this water uptake is mainly
salt free as it occurs due the ice lens pumping effect, and could possibly dilute the concentration of the chloride ions solution, affecting the profiles accordingly. However, the profiles show no such reduction in chloride concentration.

5 CONCLUSIONS

The experiments, designed to mimic real world conditions, allow for interaction of multiple transport mechanism. They are complex experiment because they combine capillary water uptake with diffusion at the same time, and overlaying these with the action of freeze-thaw. The results provide an insight into possible interaction therefore it is important to observe the outcome of verified behaviour. It can be difficult to extract a full explanation without additional experiments; however, based on the limited tests and samples tested, the following conclusions can be drawn:

- The water uptake for B52 is greater than B42, as would be expected due to the pore structure of these concretes;
- Concrete samples subject to freeze-thaw cycles have a greater uptake of water than subject to pure ponding, suggesting that micro ice lens pumping is active;
- No clear difference is noticed in the uptake of water by the intensity of the freeze-thaw cycle (low negative temperature);
- The depth and volume of B55 profiles is greater than B42 profiles, as would be expected due to the pore structure of these concretes;
- The effect of the freeze-thaw cycles on the chloride profile is small or negligible, which is surprising considering the increased water uptake that the same concrete presents. This could suggest that diffusion is occurring in saturated microstructure unaffected by the action of freeze-thaw, i.e. diffusion dominates, or, that the interaction between competing transport mechanism is complex, with no pure mechanism explaining consistently the findings, but their current interaction results in profiles identical to those of pure ponding.

ACKNOWLEDGEMENTS

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REFERENCES


