EFFECT OF COUPLED DETERIORATION MECHANISMS ON CONCRETE DURABILITY IN COLD ENVIRONMENTS

Miguel Ferreira¹, Hannele Kuosa², Markku Leivo³ and Erika Holt³

1 Senior Scientist, Lifetime Management Area, VTT Technical Research Centre of Finland, Finland
2 Research Scientist, Lifetime Management Area, VTT Technical Research Centre of Finland, Finland
3 Principal Scientist, Lifetime Management Area, VTT Technical Research Centre of Finland, Finland

ABSTRACT

The durability of concrete is traditionally assessed based on the deterioration of a single mechanism. Yet in practice, as a result of varying environmental exposure, concrete is typically affected by several deterioration mechanisms, possibly with synergetic effect on the degradation rate of concrete. Concrete infrastructure located in cold climates has to perform in rather difficult conditions due to the extremely harsh winters. This results in unique combinations of degradation mechanisms. Commonly occurring deterioration mechanisms are freeze-thaw, carbonation and chloride induced corrosion. In light of recent research more attention is now being drawn to assessing coupled deterioration mechanisms. For instance, evaluating how cracks resulting from freeze-thaw influence chloride ingress, or how carbonation changes the surface properties and thereby influencing frost-salt scaling and chloride penetration. In this paper, the results of research projects at VTT based on assessing coupling deterioration mechanisms are presented. These research projects have built on several decades of concrete durability research at VTT, including 15 years of field station studies. Durability performance has been assessed both by accelerated laboratory testing and from in situ exposure results from field stations. This research provides the background for development of service life prediction tools, and supports a holistic approach for deterioration assessment.

INTRODUCTION

The design tools available for predicting the lifetime of concrete materials are typically based on a single driving force for deterioration, such as freeze-thaw induced scaling due to de-icing salts or concrete cracking due to chloride ingress induced reinforcement corrosion. Accelerated laboratory tests are used to characterise the individual deterioration mechanisms and correlate the results with in-situ performance of structures. In reality, existing structures are subjected to numerous and simultaneous forms of deterioration. Thus laboratory simulations and deterioration predictions should take into account these multiple, interacted deterioration parameters when modelling service life.

The effect of binding material must be considered when studying the interacted deterioration of concrete. Multi-deterioration mechanisms are complicated and there is little knowledge on the real performance of concrete subject to such complex deterioration mechanisms. There are no widely accepted rules or service life models to take this into account, for instance the effect of surface carbonation and drying on the scaling caused by freeze-thaw with de-icing salt. Still it is already well known that concrete surface properties will vary according to the binding materials and cement types when exposed to e.g. atmospheric carbon dioxide and drying at dry microclimate. Recent research in Finland on multi-deterioration mechanisms of concrete included also the effect of the binding material when reasonable or possible. In the future the effect of binding materials will be a subject for the further studies.

Recent research at VTT has been undertaken with the overall objective to evaluate the effect of interacted deterioration mechanisms on the service life of concrete structures - Duraln (Deterioration Parameters on Service Life of Concrete Structures in Cold Environments, 2007 – 11) and CSLA (Concrete Service Life
Assessment, 2012 – 2015) (Leivo et al. 2011a, Ferreira et al. 2012). Typically, concrete research has focused on both field and laboratory studies. This paper presents aspect of the research performed in the laboratory using natural and accelerated testing procedures and looking at the interacted deterioration of freeze-thaw, carbonation and chloride ingress. The effect of concrete mix design, including the binding material type, is also included in some of the studies.

LABORATORY STUDIES ON THE MULTI-DETERIORATION MECHANISMS

Materials

Table 1 presents the basic information on the cements, additions and admixtures used in the laboratory studies on multi-deterioration mechanism. Acronyms used for labelling mixes are presented. Cements and blast furnace slag (BFS) were provided by Finnsementti Oy. The aggregates were good quality Finnish granitic aggregates with water absorption < 0.5 %. The effective water content (w_{eff}) was used for the w/b calculation, i.e. water absorbed by the aggregate particles was not included. (Leivo et al. 2011b, Holt & Leivo 2011, Ferreira et al. 2014a).

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Cement/addition/admixture type</th>
<th>Description</th>
<th>Blaine [m²/kg]</th>
<th>Other information</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>CEM I 42.5 N – SR3</td>
<td>Sulphate resistant cement</td>
<td>330</td>
<td>Limestone 1%</td>
</tr>
<tr>
<td>R</td>
<td>CEM I 52.5 R</td>
<td>High strength cement</td>
<td>440</td>
<td>BFS 1%; Limestone 6%</td>
</tr>
<tr>
<td>Y</td>
<td>CEM II/A–M(S–LL) 42.5 N</td>
<td>Ordinary cement</td>
<td>410</td>
<td>BFS 7%; Limestone 6%</td>
</tr>
<tr>
<td>PIKA</td>
<td>CEM II/A-LL 42.5 R</td>
<td>Rapid hardening cement</td>
<td>530</td>
<td>Limestone 2%</td>
</tr>
<tr>
<td>P</td>
<td>CEM II/B-S 42.5 N</td>
<td>Blended cement</td>
<td>380</td>
<td>BFS 27%; Limestone 2%</td>
</tr>
<tr>
<td>BFS</td>
<td>Blast Furnace Slag</td>
<td>BFS KJ400</td>
<td>400</td>
<td>Limestone 2 %</td>
</tr>
<tr>
<td>FA</td>
<td>Fly Ash</td>
<td>Fineness N, Class A</td>
<td>ca. 250</td>
<td>Complies with the demands in EN 450-1: 2005</td>
</tr>
<tr>
<td>G</td>
<td>Glenium G 51</td>
<td>Superplasticizer</td>
<td>-</td>
<td>Modified polycarboxylic ether</td>
</tr>
<tr>
<td>IP/AM</td>
<td>Ilma-Parmix/Airmix</td>
<td>Air entraining admixture</td>
<td>-</td>
<td>fatty acid soap/synthetic tensides</td>
</tr>
</tbody>
</table>

Concrete mix design

Water-binder ratios (w/b) varied between 0.42 and 0.60. The effective w/b ratio was calculated by:

\[ w_{\text{eff}} = \frac{w}{(Cement + 2 \times SF + 0.8 \times BFS + 0.4 \times FA)} \]  

(1)

The number of concrete mixtures was altogether about 40. Table 2 presents the concrete mix design ranges for the different multi-deterioration studies covered. The concretes were air entrained bridge concretes representing Finnish practice, or concretes with relatively high w/b, and in some cases also with inadequate air entrainment, to make the deterioration faster. In some cases mortars were prepared for the studies. Air content varied from 2 % (no air entrainment) to 6 %. When BFS was use, the content was 50 % of the binding material. For FA the content considered was 24 %.

Compressive strengths (28 days) varied from 27 MPa to 67 MPa. Detailed information on the mixes for the different multi-deterioration studies can be found in (Leivo et al. 2011, Ferreira et al. 2014a, Ferreira et al. 2014b). Here the mix design short code gives the most basic information on the concrete composition, e.g. “SR-BFS-06-A5” means that the binding material is composed of cement SR and BFS (see Table 1), w/b is 0.60, and air content is 5 %.
Multi-deterioration studies, testing methods and results

Effect of freeze-thaw cracking on carbonation. The aim was to understand how internal freeze–thaw damage and surface cracking affects carbonation. For this study, different degrees of internal damage were achieved with the CEN/TR 15177:2006 slab test method. The amount of freeze–thaw cycles for each specimen was selected so that the different degrees of internal deterioration, as determined by the relative dynamic modulus of elasticity (RDM) by using ultrasonic pulse transit time, was introduced. Two specimens for each concrete were removed from the freeze-thaw test at each of the RDM levels ~95%, 80%, 65%, 50% and 35% and dried at RH65% until constant weight (change in weight < 0.2 %/24h period). At the same time one reference specimen with water on top was also moved to drying. This was followed by carbonation at 1% CO₂ for 56 day. Carbonation depths were measured according to EN 13295: 2004. Some thin sections were also prepared to observe the effect of the freeze–thaw deterioration on the near surface cracking and the carbonation.

The results revealed some correlation (R² = 0.60) between the RDM and carbonation degree, as determined after the freeze–thaw testing for the mixes with high enough w/b concrete (Y-066-A0.8). As the RDM decreased from 80% to 30%, the depth of carbonated concrete increased from 3.5 mm to about 5.5 mm. The cause of this increased penetration can be attributed to surface cracking associated with the increase in internal deterioration due to freeze–thaw, as observed by thin section microscopy. For the concrete Y-050-A1.0 no effect of internal freeze-thaw deterioration on carbonation was detected, as the deterioration degree was determined by RDM. It was concluded that internal freeze-thaw deterioration will have a limited effect on carbonation, and is related to the possible surface cracking degree and type. Cracking parallel to the surface may not have a big effect on the carbonation. It can be expected that the meaning of binding material in multi-deterioration by freeze-thaw and carbonation will be the same as in the case on carbonation only. More studies are needed for reliable service life modelling with this multi-deterioration type. (Leivo et al. 2011b, Kuosa et al. 2014)

<table>
<thead>
<tr>
<th>Multi-deterioration study</th>
<th>Mix design range</th>
<th>Binding materials (see Tab. 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of freeze-thaw cracking on carbonation</td>
<td>0.50 and 0.63</td>
<td>Y</td>
</tr>
<tr>
<td>Effect of freeze-thaw on chloride penetration:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Effect of freeze-thaw cracking</td>
<td>0.50 and 0.63</td>
<td>Y</td>
</tr>
<tr>
<td>- Effects without cracking</td>
<td>0.42 and 0.55</td>
<td>SR</td>
</tr>
<tr>
<td>Effect of varying surface ageing on freeze-thaw scaling with salt</td>
<td>0.40 – 0.51 (mostly 0.42)</td>
<td>All</td>
</tr>
</tbody>
</table>

Effect of freeze-thaw on chloride penetration. Effect of freeze-thaw cracking. The aim was to understand the effect of freeze–thaw deterioration on the chloride ingress. Concretes and mortars with little or no air entrainment (Y-050-A1.0, Y-051-A2.7, Y-050-A1.3 and Y-065-A0.8) were prepared for this multi-deterioration study. Freeze–thaw damage was created by using the CEN/TR 15177:2006 slab test method. Different degrees of internal deterioration (RDM) were introduced, similar to the case of multi-deterioration by freeze-thaw and carbonation after that. Some reference specimens were without any freeze-thaw, and were maintained in water (+20°C) during the freeze-thaw. Chloride migration testing was done according to NT Build 492:1999. Specimens (Ø98 mm, h50 mm) were cored from the slabs after the freeze–thaw testing and used for the determination of the chloride migration coefficient. The test result was the chloride migration coefficient (D_{msm}) as a function of the internal freeze–thaw deterioration...
Results are presented in Figure 3. As was expected, the chloride migration increased due to the cracking, as quantified by the RDM. For instance, in the case of a high w/b (0.65) in Figure 3a), when RDM decreased from 95% to about 30%, $D_{nssm}$ increased from $27 \times 10^{-12} \text{m}^2/\text{s}$ to $37 \times 10^{-12} \text{m}^2/\text{s}$ (37%). The cracking at the surface layer exposed to the chlorides may have been primarily parallel to the surface and thus not significantly impacting the perpendicular chloride transport. In Figure 3b) the values for the RDM higher than 100 are for the specimen with no freeze-thaw, or with low deterioration in freeze-thaw. There is an increase in RDM caused by hydration (ca. 7 months). More results are needed for reliable modelling, and especially in the case of different binding materials. In this study it was not possible to find out if for instance the CEM III type cements, or the use of additions as BFS, will reduce the effect of freeze-thaw cracking on chloride migration.

![Figure 3. Effect of internal freeze-thaw damage (RDM) on the chloride migration coefficient: a) Concretes Y-051-A1.0 and Y-065-A0.8; b) Concretes Y-050-A2.7 and Y-050-A3.0](image)

**Effect of freeze-thaw on chloride penetration. Effect of freeze-thaw cyclic loading on chloride ingress.** The aim of this research project was to study the influence that freeze-thaw cycles have on chloride ingress. Recent research has shown a synergetic effect between freeze-thaw and chloride penetration, but no steps have been taken to characterize and comprehend the mechanisms involved (Kuosa et al. 2014). Two distinct concretes were subject to four different freeze-thaw test cycles and two ponding conditions. Two concrete mixes were prepared with a 0.42 and 0.55 w/b ratios (SR-042-A4 and SR-055-A6, respectively). A CEM I 42.5 N-SR3 was used to minimise the possibility of chloride binding. Four different freeze-thaw testing cycles were defined to assess influence of freeze-thaw cycles on the transport of chlorides in concrete. The first three 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/thawing was kept as close as possible to the reference test (CEN/TS 12390-9:2006). The fourth test follows the reference test curve, except that the lowest temperature point (-20 °C) was held for 60 hours, so that the total length of the cycle was 72 hours. The total number of freeze-thaw cycles was 112 for the 24 hour test cycle, and 41 cycles for the 72 hour cycle totalling 143.5 days.

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 (Ferreira et al. 2012). Two additional tests were also performed - ponding tests (natural immersion) 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.

![Figure 4. Comparison of the chloride profiles for +20 °C ponding and -20 °C freeze-thaw testing with 24 hour and 72 hour cycles. Result for the SR-055-A6 (a) and SR-042-A4 (b) concretes.](image)

The chloride profiles for concrete SR-055-6 and SR-042-A4 (Figure 4) for ponding and freeze-thaw cycles show the quality difference between the concretes (water/binder ratios), i.e., deeper chloride profile for SR-055-A6 concrete. The clear effect of testing duration is visible in all profiles. The results show small differences between the ponding profiles and the freeze-thaw profiles. This is an unexpected finding as the measured water uptake is 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 to the ice lens pumping effect, and would result in a dilution of the chloride ions solution, affecting the profiles accordingly. However, the profiles show no significant changes in chloride concentrations. This confirms the complexity of the interaction of the transport mechanism in action. A comparison of the profiles for 41/72 hour freeze-thaw cycles to 112/24 hour cycle shows similar size profiles. The number of cycles that are being compared differs greatly, and considering that the uptake of water (and chloride) is proportional to the number of cycles, this implies that other mechanisms are influencing chloride ingress.

**Effect of varying surface ageing on freeze-thaw scaling with salt.** The effect of varying surface ageing on freeze-thaw surface scaling (with salt) was studied by using natural and accelerated ageing methods. Detailed information on the exposure cases (EC) and the testing methods are presented in (Leivo et al. 2011b) and (Kuosa et al. 2012). Four different exposure cases (EC) are included here:

- **EC1:** Concrete specimens were subject to freeze-thaw test according to CEN/TS 12390-9:2006. Reference method, i.e. the slab test with 3% NaCl-solution was used. Scaling degree was recorded, and the final result was scaling after 56 cycles.
- **EC2:** Before the similar freeze-thaw as in EC1, concrete specimens were stored at relative humidity RH 65% and 20°C, with natural CO$_2$ concentration (ca. 420 ppm), for a period of approximately 1.2 – 1.3 years. At the freeze-thaw, these specimens were considered to be naturally aged, i.e. there was hydration, surface drying and carbonation.
- **EC3:** Before the similar freeze-thaw as in EC1, concrete specimens were stored for approximately 1.6 years in the same conditions as in EC2, but after that a 10 mm concrete layer was sawed off to remove the carbonated layer. The concrete specimens were considered to be aged, but not carbonated. It was also assumed that the new testing surface had a lesser drying degree than the specimens in EC2.
- **EC4:** Before the similar freeze-thaw as in EC1, the concrete specimens which were tested aged but without carbonation (EC3) were re-tested after an additional ageing procedure. In this the main aim was to get carbonated surface layer, i.e. the EC3 somewhat scaled surface was carbonated and re-
tested. In this case the ageing procedure consisted of: i) 3 month period at RH 65% and 20°C, CO₂ ca. 420 ppm; ii) accelerated carbonation at 1% CO₂ for 56 days, and iii) 11 month storage with the concrete specimens wrapped in plastic at 65% RH and 20°C (a practical reason).

The aim was to find out what effect ageing had on surface scaling as a function of the different binding materials. The effect of concrete mix design, as air content and quality, was also included. Air content was measured for fresh concrete. For hardened concrete, also the air content for small entrained air pores <0.3 mm was determined. This was by using thin sections and point count method, principally as in (VTT-TEST-R-003: 2011) for the determination of air pore content and spacing factor for air pores <0.8 mmm. The amount of small air pores is known to be decisive for the quality and effectiveness of the concrete air entrainment.

Figure 5a) presents the effect of varying surface ageing (EC1 – EC4) on freeze-thaw scaling. It can be seen that long term ageing with carbonation and drying at RH 65% (EC2) results in larger frost-salt scaling compared with standard testing (EC1) where freeze-thaw started soon after 28 days. Normally scaling after long term ageing without carbonation (EC3) is about the same as scaling in standard testing. In one case (PIKA-042-A5.0) also scaling after ageing without carbonation was higher than scaling after standard testing. Figure 5b) presents the effect of air content on scaling. It can be seen that the effect of air content on scaling is always high. Good air entrainment is needed for low scaling degree.

Figure 6 gives the amount of all the air pores in fresh concrete, i.e. total air content, and the amount of small pores (<0.3 mm) in hardened concrete. It can be seen that in some cases there are significant differences between these air contents. For instance, for the concretes R-042-A5.5 and R-040-A5.4 (w/b = 0.40 – 0.42; fresh concrete air ca. 5.5%), the air content for pores <0.3 mm in hardened concrete is 0.6 % or 2.9 %. Figure 6b) gives the scaling for these two concretes in the different ageing cases (EC1 – EC3). It can be noted that the scaling is much higher in the case of a small amount of <0.3 mm pores, compared with the case of high amount of small pores. Also multi-deterioration with carbonation and drying before freeze-thaw had less effect on the scaling if there was enough small air pores, i.e. a good air entrainment. It was also detected that for instance in the case of 50% of BFS, the effect of ageing and carbonation was not remarkable with good air entrainment (see Figures 5 and 6).

Figure 7 presents two comparisons of the scaling degrees after 56 cycles. From Figure 7a) it can be seen that the differences between EC2 (with natural long term carbonation) and EC4 (with some natural carbonation and also 56 d carbonation at 1% CO₂) were small, when the scaling was less than 1 kg/m², as
in the most cases. With higher scaling values, the scaling was more in EC4. In EC4 the time for natural carbonation and drying was only 3 months, and the surface layer carbonation was reached by accelerated carbonation at 1% CO₂, instead of 1.2 – 1.3 years drying and carbonation at RH 65% in EC2. EC4 included also an additional 11 month storage time for the specimens as wrapped in plastic. In both cases it was verified by using a phenolphthalein indicator solution that carbonation depth was more than the final depth for scaling. In all, especially carbonation was found to have a big effect on the freeze-thaw scaling with salt. Figure 7b) presents that scaling in EC3 after 1.6 years ageing without carbonation was about the same as in EC1 by the standard testing by CEN/TS 12390-9:2006 reference method. (Kuosa 2011, Kuosa et al. 2014a)

MODELLING SERVICE LIFE WITH MULTI-DETERIORATION MECHANISMS

An example of the effort to develop design tools that take into account multi-deterioration mechanisms is Ennus-Concrete. This software tool has been developed in Finland continuously for more than 8 years with the aim to assist the designer/engineer, during the decision making process, with regards to durability service life design (Ferreira et al. 2014c, Vesikari et al. 2011, Vesikari 2011, Håkkinen et al. 2007). Ennus-Concrete performs service life design determinations for the following concrete degradation mechanism: internal cracking due to freeze-thaw, freeze-thaw scaling, and corrosion initiation due to both carbonation and chloride penetration.
Ennus-Concrete also includes the determination of interaction factors, i.e., factors that take into account the interaction between different degradation mechanisms. The intention is to provide the user/designer with a methodology for such an approach to enhance their sensibility to the performance of concrete. The model is based on the factor method described in the ISO 15686-1:2011 but does not fully conform to it. The service life determination is performed as a function of the desired fractile of the service life distribution assumed to be log-normal with a coefficient of variation = 0.6. In practice, this means that, for a 50 year service life determination with a 95% confidence, the average service life must be $2.9 \times 50 = 145$ years.

When concrete is subject to internal cracking due to freeze-thaw loading, it is assumed that the carbonation coefficient increases with the increase in internal damage of the concrete. The coefficients for carbonation ($k_{ca,IF}$) and chloride ingress ($k_{cl,IF}$) of concrete subject to freeze-thaw induced cracking increase with time and increasing freeze-thaw deterioration of concrete (Vesikari 2009). Figure 9 presents the empirical relationship between the carbonation depth and the RDM (a), or between the chloride ingress and RDM (b). For the carbonation/freeze-thaw interaction factor, the following empirical relationship has been suggested based on the data reported in (Leivo et al. 2011b):

$$I_{ca,IF} = \frac{k_{ca,IF}}{k_{ca}} = 1 + 0.64 \left( 1 - \frac{RDM}{100} \right)^{132}$$

(2)

where

$I_{ca,IF}$ is the interaction factor for carbonation and internal damage by freeze-thaw (-);

$k_{ca}$ is the carbonation coefficient of unaffected concrete (mm/year$^{0.5}$);

$k_{ca,IF}$ is the carbonation coefficient of concrete subject to freeze-thaw induced cracking (mm/year$^{0.5}$), and

$RDM$ relative dynamic modulus of concrete (%).

For the chloride migration/freeze-thaw interaction factor, the following empirical relationship has been suggested based on the data reported in (Leivo et al. 2011b):

$$I_{cl,IF} = \frac{k_{cl,IF}}{k_{cl}} = 1 + 0.30 \left( 1 - \frac{RDM}{100} \right)^{0.93}$$

(3)

where

$I_{cl,IF}$ is the interaction factor for chloride ingress and internal damage by freeze-thaw (-);

$k_{cl}$ is the chloride ingress coefficient of unaffected concrete (mm/year$^{0.5}$);

$k_{cl,IF}$ is the chloride ingress coefficient of concrete subject to freeze-thaw induced cracking (mm/year$^{0.5}$), and

$RDM$ relative dynamic modulus of concrete (%).
The relationships presented in Equations 2 & 3 are not representative of all cement types or all water/binder ratios, while they are dependent on the thickness of concrete cover.

CONCLUSIONS

This paper presents an assortment of research results which evaluate the effect of interacted deterioration mechanisms on the service life of concrete structures. The following are some considerations on the interaction between different deterioration mechanisms:

• **Freeze-thaw/carbonation** - Freeze-thaw deterioration had a limited effect on carbonation. Increased carbonation was expected to be related to the type and amount of surface cracking, as measured by RDM. However, cracking was found to be parallel to the surface which has a minor effect on carbonation. It can be expected that the effect of binding material in freeze-thaw/carbonation will be similar as in the case of only carbonation. More studies are needed for reliable service life modelling with this multi-deterioration type.

• **Freeze-thaw/chloride migration coefficient** - The chloride migration coefficient (Dnssm) increased due to freeze-thaw cracking, as quantified by the RDM. A clear trend was detected based on all the results. This trend has been exploited in preliminary models for multi-deterioration in the case of freeze-thaw cracking and chloride ingress. More results are needed for reliable modelling, and especially in the case of different binding materials. In this study it was not possible to find out if for instance the CEM III type cements, or the use of additions as BFS, will reduce the effect of freeze-thaw cracking on chloride migration.

• **Freeze-thaw/chloride profiles** - The results of the study of the effect of freeze-thaw cyclic loading on chloride ingress show a small difference between the ponding profiles and the freeze-thaw profiles. This is an unexpected finding as the water uptake is larger for the concretes with one day freeze-thaw cycles than with just ponding. Furthermore, concretes subject to freeze-thaw cycles tests have higher chloride volumes at the surface compared to the chloride profiles of the concretes subject to ponding. This difference could result from the freeze-thaw pumping contribution to chloride ingress. Deeper in the concrete, the chloride profiles of the ponding specimens exhibit higher values indicating that the effect of diffusion is dominating.

• **Freeze-thaw/surface ageing** - Surface ageing had a considerable effect on the degree of freeze-thaw surface scaling. This effect varied according to concrete quality, binder type and air entrainment. Concrete ageing, and especially carbonation, should be considered both in the concrete quality control and in service life design. It is recommended that new laboratory standards for freeze–thaw testing should be generated to account for e.g. accelerated ageing and carbonation procedures before the freeze–thaw exposure in order to accurately simulate field conditions. This multi-deterioration type should be included in reliable service life models.

• **Modelling of service life with multi-deterioration mechanisms** - A procedure for determining the interaction factor of combined degradation mechanisms is briefly described. The effect of freeze-thaw induced damage on the rate of carbonation/chloride penetration is clearly observed. Caution is recommended when interpreting the results as they are based on a limited number of cement types and concrete quality. Results showed that, if frost attack is rapid, it is usually the dominating degradation mechanism, relegating reinforcement corrosion initiated by carbonation/chloride penetration. If frost attack proceeds slowly, reinforcement corrosion becomes dominate, and the interaction effects should be considered in the service life design of RCS.

The on-going Finnish concrete durability field testing includes inherently many interacted deterioration mechanisms, as determined by the combined exposure types at the different testing sites. To get reliable field testing data on the effect of the binding material, field testing must be long term, i.e. hydration and ageing must be included, and there must be enough data for the modelling. In addition, the results must be carefully analysed taking into account all the concrete mix design and exposure parameters at the same time.
ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding received from TEKES (The Finnish Funding Agency for Technology and Innovation), and the Finnish concrete and cement industry. Research cooperation with Aalto University is also acknowledged.

REFERENCES

NT Build 492. 1999. Concrete, mortar and cement-based materials: Chloride migration coefficient from non-steady-state migration experiments. 8 p.