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CONCRETE DURABILITY BASED ON COUPLED DETERIORATION BY FROST, CARBONATION AND CHLORIDE

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ABSTRACT

Concrete performance is traditionally assessed based on deterioration caused by a single mechanism. Yet in field performance, concrete is actually being affected by simultaneous environmental and conditional exposures, possibly with synergetic effect on the degradation rate of concrete.

In this paper, the results of a Finnish research project based on assessing coupling deterioration mechanisms are presented. For instance, evaluating how cracks resulting from frost attack influence chloride ingress, or how carbonation changes the surface properties and thus may affect frost-salt scaling and chloride penetration. The research project built on 30+ years of concrete durability research, including 10 years of field station studies. The durability performance was assesses with both accelerated laboratory testing and *in situ* exposure results from field stations, to more realistically predict long-term performance. All the results together with local weather data served as a basis for thorough modelling, computer simulation and development of service life models.

The project was composed of an extensive laboratory testing regime, in parallel to the exposure of several concrete specimens at field stations, also subject to periodic testing. Testing was based on standardized methods, taking into account the effects of ageing and repeated exposure cycles to different conditions as well as field studies. More than 60 different normal strength concrete mixtures were evaluated with a range of cementitious binders and air contents.

The final stage of the project addressed improving service life prediction tools based on the laboratory coupled deterioration results. The project results quantitatively support the hypothesis that a holistic approach should be taken to predicting deterioration. The project has addressed improving service life prediction tools based on the laboratory coupled deterioration results and field testing.

Key-words: durability, frost, frost-salt, carbonation, chloride, coupled/interacted deterioration, service life, field testing.

INTRODUCTION

When durability of concrete is evaluated, many types of exposure or attack may be considered to influence the structural performance. Yet tools for predicting the lifetime of concrete materials are typically based on one driving force of the deterioration, such as spalling due to de-icer salt with frost exposure or cracking caused by chloride ingress and subsequent reinforcement corrosion. Accelerated laboratory tests are used to test these individual deterioration mechanisms and correlate the results to real-time performance of structures. In reality, existing structures are subjected to numerous and sometimes simultaneous forms of deterioration in their relative environments. Thus laboratory simulations and deterioration predictions should take into account these multiple, interacted deterioration parameters when modelling service life.

A three year Finnish research project recently completed investigated the deterioration of concrete when subjected to coupled deterioration mechanisms. The DuraInt – Deterioration Parameters on Service Life of Concrete Structures in Cold Environments (2008 - 2011) research project was undertaken by VTT Technical Research Centre of Finland in cooperation with the Department of Civil and Structural Engineering of the University of Aalto. The overall objective of the project was to evaluate the effect of interacted deterioration parameters on the service life of concrete structures. The project was structured into five main tasks:

- Task 1: State of the art [1],
- Task 2: Long term field testing [2, 6],
- Task 3: Laboratory testing with interaction [3, 7],
- Task 4: Deterioration models with interaction [4],
- Task 5: Service life models with interaction [5, 8] and
- Task 6. International co-operation.

Here only some selected examples are shortly presented from the project results to give an idea of the project contents [1 – 5]. The project also included cooperation with on-going concrete durability research in the USA, Canada, Norway, Sweden and Portugal.

FIELD TESTING FOR CONCRETE DURABILITY

Field testing results are considered necessary to get relevant information on concrete durability in field conditions. Yet in most cases direct comparison of field testing results with standardized laboratory testing results is not applicable. This is because of the interaction of different deterioration mechanics at the field. Instead deterioration modelling with interaction is needed. For quality control purposes modification of laboratory testing methods for better comparability with field deterioration was also desirable. Field testing in this project included interacted deterioration along with considering the effects of e.g. moisture, salt exposure, temperature and solar radiation variations and effects of carbon dioxide and hydration with time.

In Finland there are three concrete durability field testing areas under evaluation. [2, 6] Two of these are located in southern Finland in the city of Espoo and along highway 7 near Kotka (Figure 1a) and one in northern Finland in the town of Sodankylä. Two of the field stations include concretes where frost and carbonation are evaluated and the highway field station includes concrete samples for assessing frost-salt deterioration, carbonation and chloride penetration. Sheltered carbonation studies were also performed at the Espoo site, i.e. the specimens were under a roof on wooden racks (Figure 1b). In autumn 2009 some parallel concrete specimens were also delivered to a similar highway testing field in Borås, Sweden.

The aim is that field testing will continue for at least 20 years in all of these field stations. New materials are also being added on an annual basis to serve the Finnish concrete industry´s needs.

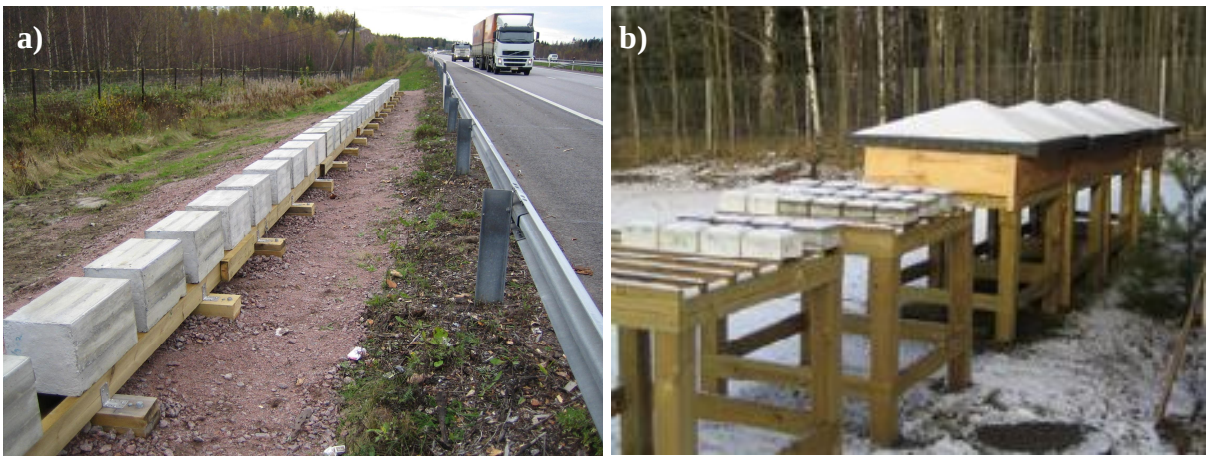


Figure 1 - DuraInt field exposure sites (a) next to Highway 7, Kotka; (b) Otaniemi, Espoo.

In the project chloride penetration, sheltered carbonation and freeze-thaw attack with and without salt were studied. Both freeze thaw studies with salt and chloride penetration studies were at the HW 7 field in Southern Finland.

The first winter (2007 - 08) during the DuraInt project was mild in Finland, but with many (83) fluctuations around 0 ^{o}C. The second (2008 - 09) winter was closer to the average winter in Finland with also many (80) freeze thaw cycles below 0 ^{o}C but including also e.g. 25 cycles below -5 ^{o}C and 9 cycles below -10 ^{o}C. The third winter (2009 - 10) was colder than normal in southern Finland. There were only 59 freeze-thaw cycles below 0 ^{o}C but also 4 long periods below -20 ^{o}C and one below -25 ^{o}C.

In Southern Finland, highway de-icing is normally between October/November and April. The de-icing salt used in the HW 7 field during the project was mainly sodium chloride (NaCl), which was spread in crystalline form. Also some $CaCl_2$-solution was used as a preventive measure. HW 7 field maintenance was performed to guarantee that salty splash water and water vapour can freely access exposed concrete specimen surfaces. For the frost-salt specimens it was considered essential that their upper surface was exposed to salt and water. For the chloride penetration specimens both the surface facing to the highway and the upper surface were considered as exposed surfaces and were kept free. Field weather data was collected as well as data on highway salting.

The intensive field testing work performed resulted in an extensive amount of data collected, analysed and reported [2]. Only selected results are presented in this paper, in an attempt to show the different aspects of the work performed related to different mechanisms.

Materials, concretes and characteristics

More than 30 concrete mixes were cast and placed at the exposure sites. The amount of field specimens was multifold as several parallel specimens and some specific studies with e.g. modified specimen surfaces or exposure distances were included. Full details concerning the concrete composition and specimen can be found in [2]. The concretes represent mainly prevailing common industrial mixes in Finland, with an effective water-to-binder ratio (w/b) from 0.39 to 0.60. Over half of the mixes were with a w/b ratio close to 0.42. Common Finnish cements manufactured by Finnsementti Oy, blast furnace slag (BFS) and fly ash (FA) were used. In the calculation of w/b the amount of BFS was taken as multiplied by 0.80 and FA was taken as multiplied by 0.30 ($w/b = W_{eff}/(Cement + 0.80\ BFS + 0.40\ FA)$). Most mixes were air entrained bridge concretes for the highway testing field. Fresh concrete air content was from 1.7 – 7.3 %. About 60 % of the concretes were with 4.0 % – 6.0 % air. All relevant fresh and hardened concrete properties were determined, such as slump and compressive strength. [2]

Chloride penetration

The results presented here are taken from the HW 7 field exposure site. Chloride profiles were measured after the 1st winter (2007 - 08 or 2009 - 10) and usually also after the 3rd (2009 - 10) winter season. For chloride analysis, cylinders (ø 100 mm, h >100 mm) were cored from the field specimen. Powder samples were taken from these cylinders for chloride content analyses by a profile grinding method and by dry-slicing and by grinding the slices afterwards.

Evolution of the chloride profiles is presented in Figure 2, i.e. the chloride profiles for concrete specimens with some selected binding materials and w/b ratios after the 1st and 3rd winter season. The chloride profiles represent the specimen vertical surfaces facing to the highway. Figure 3 presents the chloride migration coefficients (D_{nssm}) for these concretes. The coefficients were measured at 3 months of age by the CTH-method [9]. The effect of binding material and w/b ratio can be seen clearly in Figure 3, especially with regard to the beneficial effect of BFS and FA.

Comparing visually the profiles after the 1st and 3rd winter season, it can be seen that there is a shift inwards from the surface of the concrete (Figure 2). The average surface layer (0 – 5 mm) concentration was about 30 % higher after the 3rd winter season compared with the 1st winter season, but the difference evened out deeper in the concrete, and disappeared at about 10 mm depth. It can also be seen that the near surface chloride concentration (0 - 1 mm) is usually lower than the maximum concentration at 1.5 mm. Chloride profile determination was just before the summer time, and it can be expected that some chlorides may have already been washed away after the winter season. In addition there may have been some interaction with the near surface carbonation. Carbonation changes the surface layer pore structure and also releases chlorides. These changes are different for different binding materials. It can be seen that for concretes including BFS or FA the surface and maximum chloride content is higher than for the mixes without BFS or FA with about the same w/b ratio (0.42 – 0.45). In spite of this, the chloride content at 10 mm was already the same for all these mixes. On the other hand, in mixes with a higher w/b ratio (0.49 – 0.51) the chloride penetration depth was higher, especially after 3 winters (about 20 mm). Also, after 3 winters the chloride content at 15 mm was double for the mixtures with about w/b ratio 0.50, compared with the mixes with a w/b ratio from 0.42 to 0.45.

It is expected that after additional years the results will be more stable, and then closer analysis will give valuable information on the field chloride penetration when interacted with surface layer carbonation and possible frost action.

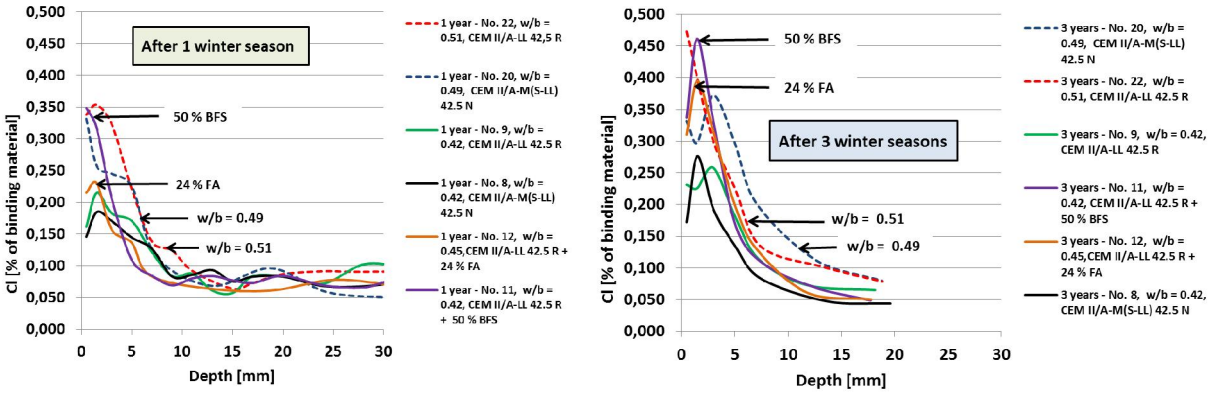


Figure 2 – Highway field chloride profiles after the 1st and 3rd winter season.

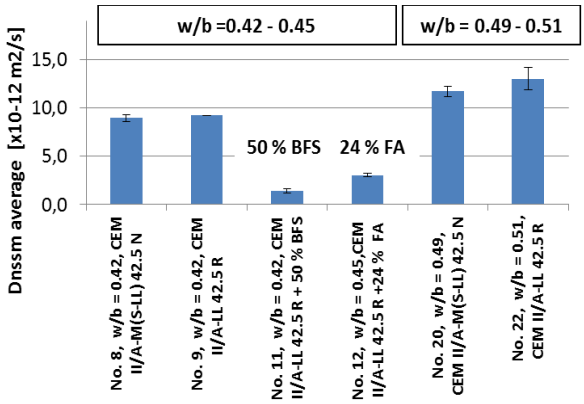


Figure 3 – Chloride migration coefficient (D_{nssm}) according to the CTH method [9]. Average values for three specimens. The values can be considered normal regarding the binding material, w/b ratio and concrete testing age (90 d).

Carbonation

The results presented for carbonation are taken from the concretes at the Espoo field exposure site. The aim of these test series was to assess the correlation between field exposure and both accelerated and non-accelerated laboratory testing results regarding the effect of binding material, w/b ratio and air content on concrete carbonation. There were 22 concrete mix designs for the carbonation studies including 8 different binding materials and three w/b ratios (0.42, 0.50 and 0.60). Most mixes were with air entrainment.

Figure 4 presents the carbonation depth for naturally carbonated field specimens and also for laboratory specimens at RH 65% as a function of carbonation depth at accelerated 1 % CO_2 exposure (for 56 days). The correlation between the laboratory carbonation at RH 65 % (ca. 8.3 months) and accelerated carbonation was good (R^2 = 0.95). For the field carbonation and the accelerated carbonation the correlation was also clear. After about 9 months of field carbonation the correlation was 0.69, and after about 2 years field carbonation the correlation improved slightly to 0.73.

For many mixes with w/b = 0.42 the field carbonation depth was less than 0.5 mm after 2.1 years. Instead for a concrete with w/b = 0.60 the depth was 4 mm. The average field carbonation depth was 0.7 mm for the mixes with w/b about 0.42. The average carbonation depth for the mixes with

a w/b from 0.46 to 0.60 was 1.4 mm. Clear effects of binding material were detected. Mixtures made with cement CEM I had low carbonation depth. Though not presented here, concrete with excessive air content had greater carbonation depths both at the field and in the laboratory accelerated (1 % CO_2) and non-accelerated carbonation exposure conditions. Figure 5 presents the carbonation depths for some concrete with different binding materials with varying w/b ratios.

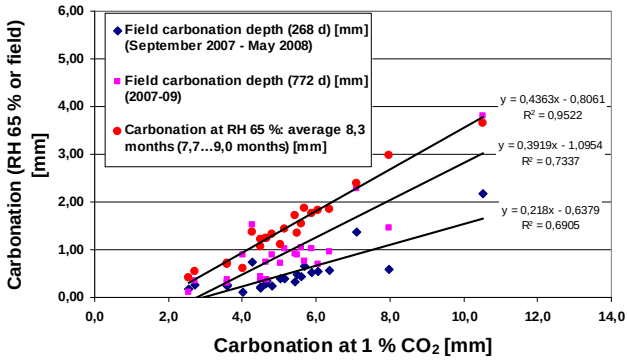


Figure 4 - Carbonation depth for naturally carbonated field specimen and for lab specimen at RH 65 % as a function of carbonation depth at accelerated 1 % CO_2 exposure (56 days).

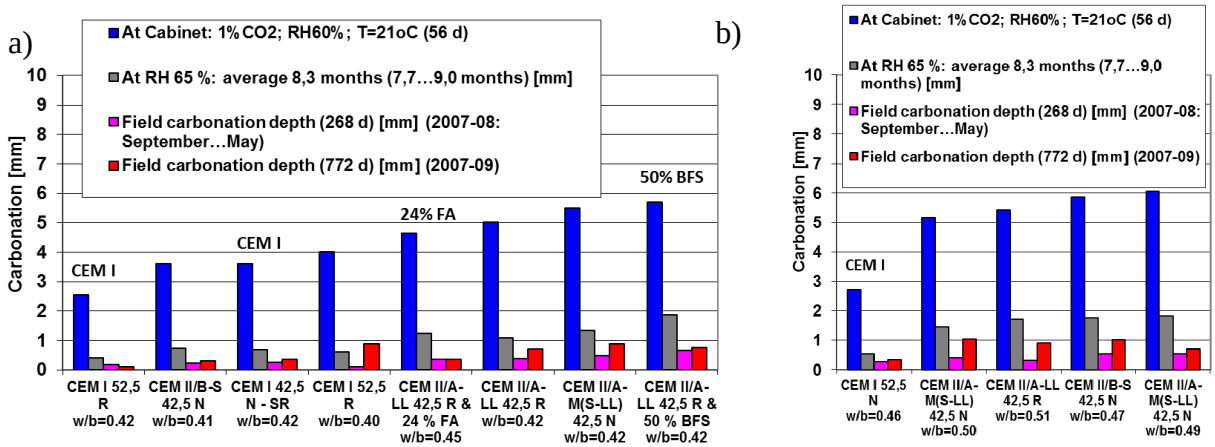


Figure 5 - Carbonation depths for concrete with different binding materials: (a) w/b 0.40 – 0.45, and (b) w/b 0.46 – 0.51. Carbonation depth is sorted by carbonation value when stored at 1 % CO_2 (56 d).

Frost-salt and frost attack – internal cracking and surface scaling

The results presented for frost salt attack are taken from concretes at the HW 7 field exposure site. Figure 6 represent the performance of the concrete during the first few years of exposure when subject to frost attack in an environment with de-icing salts. Relative dynamic modulus (RDM) was measured by fundamental frequency (FF). A positive volume change means increased size attributed to either cracking or swelling associated with moisture gain. Because both the RDM-values and volume changes are quite similar for most of the concretes (small increase or decrease), it can be expected that they are caused by other reasons than scaling and cracking at this early phase of field testing. Presumably they are caused by strength gain, moisture and salt content variation, swelling and shrinkage. It can be seen that it was possible to reliably measure very small changes in field specimens. This means that it will be possible to detect future field deterioration reliably.

For field specimens exposed to plain frost attack (no de-icing salts), no severe degradation was

visible within the 3 years of the project, due to the short exposure period of only a few winters seasons. In fact, many concretes, including somewhat unexpected also some mixtures with w/b = 0.42 but with no or low quality air entrainment, showed an increase in RDM which can be attributed to a higher degree of hydration compared to the degree of hydration at the time of the first measurement. These plain frost field measurement results are not presented here but in the project report [2].

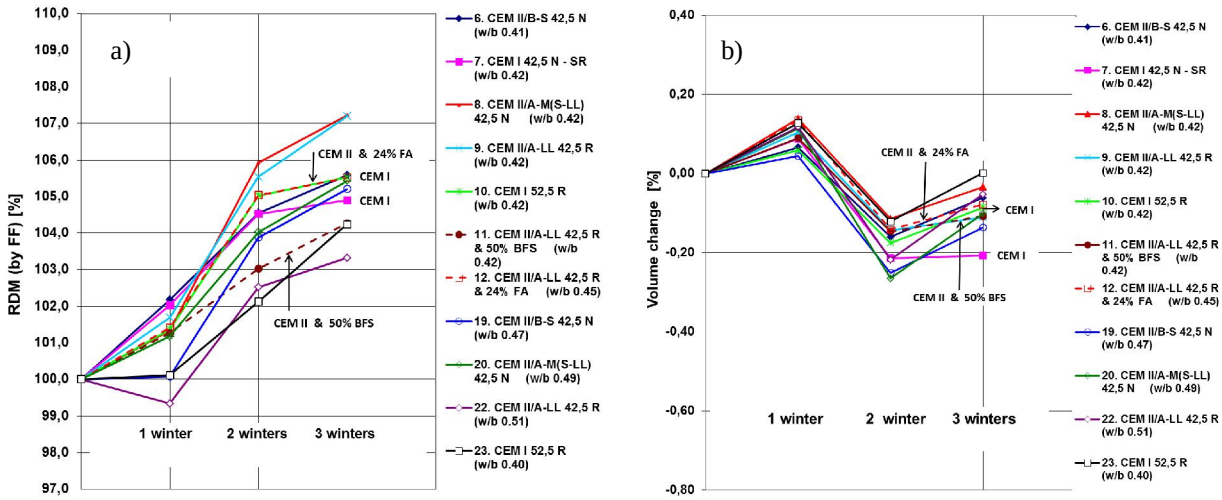


Figure 6 – Concrete results for freeze-thaw with salt at Highway 7 station (2007 - 2010). a) Average relative dynamic modulus (RDM) by fundamental frequency (3 specimens) after three winters, and b) average volume change (3 specimens). Positive (+) volume change means increase of volume.

LABORATORY TESTING WITH INTERACTION

Methods and materials

The laboratory tests were designed to investigate the coupled interaction of deterioration mechanisms. This included evaluation of internal damage due to frost, scaling due to frost-salt attack, chloride ingress, and carbonation. A schematic representation of the laboratory test program is showed in Figure 7. The project was divided into 5 parts, A - E, with different interaction. When reasonable, these interactions were cross-studied. For instance both the effect of chloride penetration on carbonation, and the effect of carbonation on chloride penetration, was studied.

About 30 different normal strength concretes and in some cases also mortar mixtures were evaluated with coupled deterioration attack. In some additional studies of carbonation cement paste mixtures were also used. Full details of the mixture designs as well as fresh and hardened mixture properties are presented in the project reports. [2, 3].

Mainly standardized laboratory testing methods were used. Frost and frost-salt testing was done according to the slab test methods [10, 11] to assess internal damage and surface scaling. Carbonation was tested at room exposure (RH 65%, 20°C), and at 1 % or 4 % CO_2 at RH 60 % (20 ^{o}C), and carbonation depth was measured using phenolphthalein indicator solution [12]. The chloride penetration and migration coefficient were measured with the CTH method [9]. In some studies water immersion, pressure saturation and weighing methods were used to get specimen moisture content, volume and pore volume information. Optical microscopy with thin section

studies were also used to assess the concrete air pore structure, cracking and carbonation. Chemical changes caused by carbonation and chlorides were analysed by using X-ray diffractometry and thermal analysis. These results are not included here, but can be found in the project report [2, 3]. Some examples of key lab results are presented here.

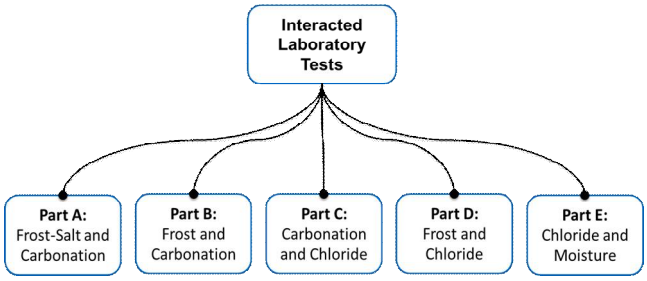


Figure 7. - Schematic representation of the interacted laboratory test program.

Interacted frost-salt and carbonation studies

The goal of the interacted frost-salt and carbonation studies was to understand how the concrete surface layer ageing and especially carbonation affect frost-salt scaling. One future aim is to find if the correlation of laboratory testing with field testing is improved when aged specimen surfaces are used in testing. Several test series were included. Also cyclic testing was used, i.e. first freeze-thaw, then carbonation, and after that again freeze-thaw exposure [3].

Figure 8 gives some selected results from a testing series including 17 concrete mixtures. Scaling after 56 cycles is presented. The difference between these methods was in the different ageing of especially the surface layer of the concrete specimen before the actual freeze-thaw phase. Frost testing was after three different pre-handling methods:

1. Testing by the standard method and procedure starting at 28 d with the re-saturation of the specimens [11].
2. Testing using concretes as ´aged and carbonated´. Testing was after about 1.3 years at RH 65%, i.e. including also surface drying at RH 65 % and 20 ^{o}C. Testing was started normally, by re-saturation of the specimens.
3. Testing using concretes as ´aged but not carbonated´. In this case a 10 mm surface layer was sawn off to remove the carbonated layer resulting from the 65 % RH storage (at age of about 1.6 years). Also the surface drying degree was presumably smaller than in the testing of case 2 above. Testing was started by normal re-saturation of the specimens as soon as possible after the sawing. Only minor surface carbonation (< 2 days at RH 65 %) was possible.

As expected, surface ageing had a considerable effect on the frost-salt scaling degree. This effect was different for different concretes with different binding materials and air pore structures [2, 3]. In the future 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.

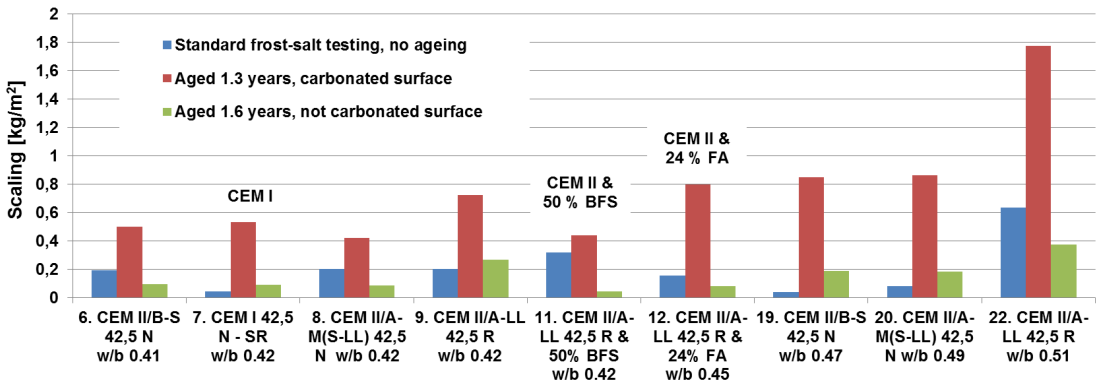


Figure 8. – Standard freeze-thaw resistance with de-icing salt (scaling, 56 cycles) by slab test [11], and by two modified methods, with aged and carbonated surface and with aged but not carbonated surface. Surface carbonation at RH 65 % (1.3 years) considerably increased the frost-salt scaling degree.

Interacted frost and carbonation studies

The main aim of these laboratory test series was to understand how frost deterioration affects carbonation. Some concrete and mortar mixtures with w/b 0.50 – 0.65 were tested. Frost deterioration to different degrees of deterioration was created by using the slab test method [10]. The amount of freeze-thaw cycles for the 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. Carbonation was at 1 % CO_2 at RH 60 % (56 d). Some thin sections were prepared to study the effect of the frost deterioration on the near surface cracking and the carbonation.

There was some correlation (R^2 = 0.60) between the internal deterioration (RDM) and carbonation degree as determined after the frost testing for the mixes with high enough w/b ratios (0.65). When the degree of frost deterioration degreased from RDM at about 80 % to about 30 %, surface carbonation was increased by about 70 % (from 3.5 mm to about 5.5 mm). Based on the thin section studies this was caused by the surface cracking associated with the measured internal deterioration (RDM) and cracking (Figure 9). It would be beneficial to have more studies prior to detailed modelling of the effect of frost attack on carbonation (see service life section).

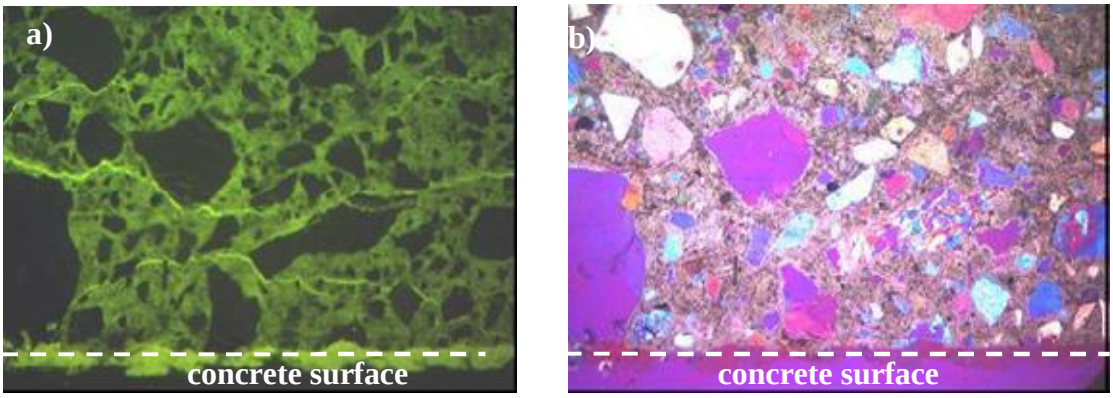


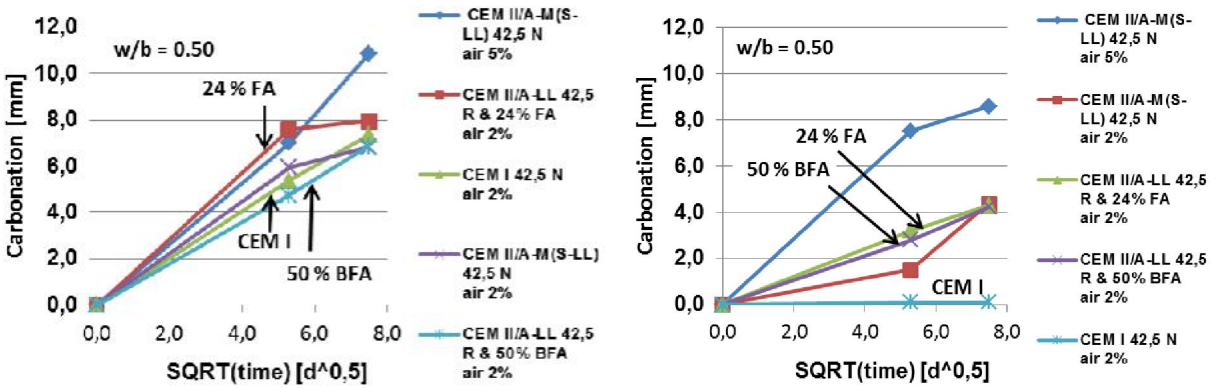
Figure 9 – Concrete with interacted frost and carbonation attack. Thin section photos representing the same about 2.5 mm thick surface layer in a concrete specimen. Concrete surface is downwards. Surface cracking is visible in UV-light (a). Carbonation is visible in polarized light (b) and detectable because of the light brown colour.

Interacted carbonation and chloride studies

The aim of these laboratory test series was to assess the effect of chlorides on the carbonation, and also the reverse for the effect of carbonation on chloride penetration.

When chloride exposure was before carbonation, the penetration was achieved by the accelerated migration test [9]. Then the concrete specimens were put to climatic room with RH 65 % and 20 ^{o}C for 1.6 months to dry (weight change < 0.2 % per day) before the accelerated carbonation testing. Accelerated carbonation was achieved by exposure at 4 % CO_2 and RH 60 %, and the reference was measured on specimens exposed to carbonation alone without the prior chloride penetration. For this, the same testing and specimens were used as for the testing of carbonation after chloride penetration. In this case the carbonated specimen surface was without chloride penetration in the chloride migration testing (i.e. NaOH-side in the testing [8]). Additional reference specimens were without any chloride testing. The concrete carbonation results after the chloride migration testing both without (a) and with (b) chlorides are presented in Figure 10. The concrete carbonation results in Figure 10a) without chlorides, i.e. for the NaOH-side of the specimen, were basically identical to the carbonation results without any chloride migration testing [3, 7].

The effect of chlorides was lower carbonation in the concrete than mixtures without chloride exposure. In CEM I 42.5 N mixtures, the carbonation was minimal when there was first accelerated migration testing followed by carbonation. The reason for this can be higher concrete moisture content/RH and water film thickness inside the pores due to chloride hygroscopy, thus decreasing the carbonation rate. Pores may also become blocked as a result of the salt crystallization in the pores network. Concrete with CEM I 42.5 N (sulphate resistant (SR)-cement) has low chloride binding capacity and this may be the reason for minimal carbonation when chlorides were introduced to the concrete before carbonation.



a) b)

Figure 10 – a) Carbonation without chloride penetration (exposed to NaOH in the preceding chloride migration testing) and b) carbonation after chloride penetration in the chloride migration testing (exposed to NaCl in the preceding chloride migration testing).

The effect of carbonation on the chloride penetration was also studied by using concretes and mortars. In a testing series with three mortars, the aim was to find out the effect of the carbonated skin layer on the chloride penetration and differences between the selected binding materials. Mortars (w/b = 0.50) were made of either only cement (CEM II/A-M(S-LL) 42.5), or then also with blast furnace slag (50 % BFS) or fly ash (24 % FA). Before chloride migration testing, the specimen surfaces were either carbonated or not carbonated. Carbonation was in a chamber with 4 % CO_2 (RH 60 %) for 157 days. The applied voltage and test duration was the same for the carbonated and non-carbonated parallel specimens with the same mortar mix design but not for

the specimens with different binding materials. The voltage was lower and the testing time was shorter for the mortar with only cement as the binding material. Chloride penetration was made visible with silver nitrate and chloride migration values (D_{nssm}) were calculated according to [9]. More detailed information on the testing procedure is presented in Task 3 reporting [3].

The carbonation depth in the carbonated specimen as well as the chloride penetration after the migration testing both with and without carbonation are presented in Figure 11a. The calculated migration coefficients (D_{nssm}, [9]) are also presented in Figure 11b. It can be seen that the carbonated surface layer in the mortars increased the chloride migration depth. This increase was most clear for the mortar containing fly ash. It must be noted that the calculated migration coefficients were much lower for the mortars with BFS and FA, both with and without a carbonated surface layer, than for the mortar made with only cement.

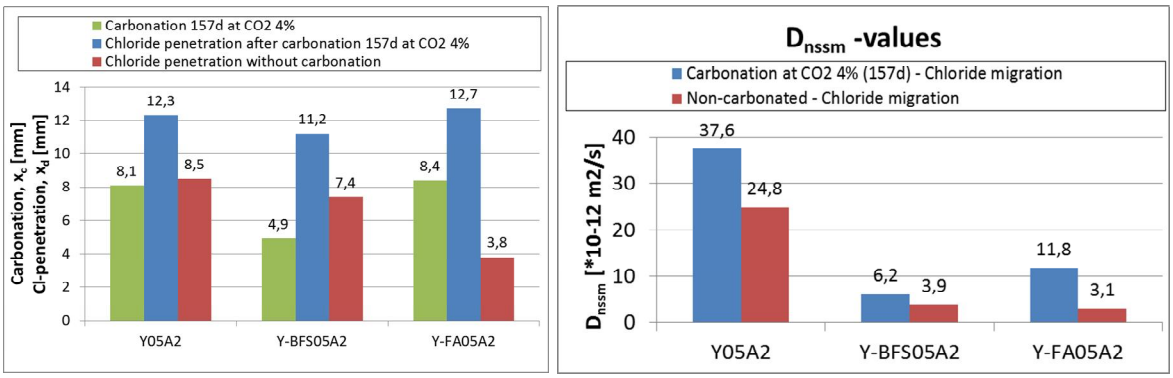


Figure 11 – a) The effect of surface carbonation on the chloride migration. Carbonation depth in the carbonated specimen, and the chloride penetration after migration testing for the carbonated and non-carbonated specimen (h50 mm). b) The effect of surface layer carbonation on the calculated migration coefficients (D_{nssm})[9].

Interacted frost and chloride studies

The aim of this laboratory test series was to better understand the effect of frost attack on the chloride ingress. Concretes and mortars (CEM II/A-M(S-LL) 42.5, w/b = 0.50 or 0.65) with very low or with no air entrainment were prepared for this interacted testing. Frost deterioration was created by using the slab test method [9]. Different degrees of internal deterioration (RDM) were introduced similar to the case of interacted frost-carbonation studies (see previous section). Chloride migration testing was again according to [9]. Specimen (ø98 mm, h50 mm) were cored from the slabs after the frost testing and used for the determination of the chloride migration coefficient.

The result in this testing was the chloride migration coefficient (D_{nssm}, [9]) as a function of the internal frost damage. One example is presented in Figure 12. As was expected, the chloride migration increased due to microcracks, as quantified by the relative dynamic modulus of elasticity (RDM). For instance in the case of a high w/b in Figure 12, when RDM decreased from 95 % to about 30 % (32 %), D_{nssm} increased from 27×10^{-12} m^2/s to 37×10^{-12} m^2/s (37 %). The trend was not as evident in other mixtures and was not as severe as expected. The cracking at the surface layer exposed to the chlorides may have been primarily parallel to the surface and thus not significantly impacting the chloride transport.

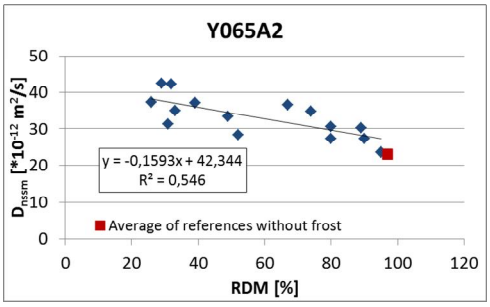


Figure 12 - Effect of internal damage presented as relative dynamic modulus of elasticity (RDM) on the chloride migration coefficient. Concrete (Y065A2) with CEM II/A-M(S-LL) 42,5, with no air entrainment and with w/b 0.65. [3]

SERVICE LIFE DESIGN WITH INTERACTION

The overall objective of modifying service life design tools was to account for the combined effects of frost attack on other types of degradation in concrete structures, namely carbonation and chloride penetration. The results were applied to practical service life design, where a special effort was made to determine the interaction factors for service life models based on the factorial approach. By use of interaction factors, the accelerating effect of frost attack on other types of degradation was taken into account. An example of the proposed model is given below, where the effect of internal frost attack on carbonation is considered. Other service life modifications in the project included interaction of carbonation-chloride and scaling by frost-salt attack (field testing studies). Further results of these aspects can be found in [5, 8].

Modelling the effect of internal frost attack on carbonation

Based on the square root of time formula (1), the increase of carbonation in an increment of time can be presented as:

$$\Delta x_{ca} = \frac{k_{ca}^2}{2 \cdot x_{ca}} \cdot \Delta t \qquad (1)$$

where

Δx_{ca}	is the increase of carbonation depth during the time step t, t+Δt, mm,
x_{ca}	depth of carbonation, mm;
t	age of concrete, years, and
k_{ca}	coefficient of carbonation, mm/a$^{0.5}$.

The total carbonation depth can be determined by totalling the incremental depths of carbonation as follows:

$$x_{ca}(t) = \sum \Delta x_{ca}$$
$$\Delta x_{ca}(t, t+\Delta t) = \frac{k_{ca}^2}{2} \cdot \frac{1}{x_{ca}(t)} \cdot \Delta t \qquad (2)$$

The increase of the carbonation is thus proportional to the square of the carbonation coefficient and inversely proportional to the carbonation depth itself. In the case of concrete exposed to internal frost attack, the carbonation coefficient increases with the increasing internal damage in concrete. Even in that case, Eq. (2) can be assumed to apply. The total carbonation depth is

determined as the sum of incremental carbonation depths which are determined from Eq. (3). The carbonation coefficient $k_{ca;IntFr}$ increases with time with increasing frost deterioration in concrete [1]:

$$x_{ca;IntFr} = \sum \Delta x_{ca;IntFr}$$
$$\Delta x_{ca;IntFr}(t, t+\Delta t) = \frac{k^2_{ca;IntFr}(t)}{2} \cdot \frac{1}{x_{ca;IntFr}(t)} \cdot \Delta t \qquad (3)$$

where:

$k_{ca;IntFr}$ carbonation coefficient of concrete which is attacked by internal frost damage (dependent on time), mm/a$^{0.5}$, and

$x_{ca;IntFr}$ depth of carbonation in internally damaged concrete, mm.

The data used for determining the relationship between the performance indicator for carbonation and internal frost attack is reported in [3]. It is based on concretes with varying w/b ratios (0.50-0.60, for CEM II/A-M(S-LL) 42.5 N, and 0.65 for CEM I 42.5 N SR with slag).

The carbonation coefficient of concrete is directly proportional to the depth of carbonation. The following empirical relationship is suggested for the frost-interacted carbonation coefficient and the original carbonation coefficient, as an average. Based on the data analysed the coefficients in Eq.(4) are determined. The relationship presented in Eq.(4) is not representative of all cement types. Additional data is required to be able to model the relationship by cement type including the influence of w/b ratio.

$$\frac{k_{ca;IntFr}}{k_{ca0}} = 1 + 0.64 \cdot \left(1 - \frac{RDM}{100}\right)^{1.32} \qquad (4)$$

where

k_{ca0} carbonation coefficient of intact concrete, mm/√year;

$k_{ca;IntFr}$ carbonation coefficient of frost interacted concrete, mm/√year, and

RDM relative dynamic modulus of concrete, %.

Assuming that the internal damage of concrete increases linearly with time between the start of the service life until the end of service life and assuming that the limit state of service life with respect to internal frost attack is 2/3 of the original relative dynamic modulus, the following equation can be written:

$$RDM(t) = 100 - 33.3 \cdot \frac{t}{t_{L;\mathrm{int}\,Fr}} \qquad (5)$$

where

$t_{L;IntFr}$ predicted service life of the structure with respect to internal frost attack, and

t time, years.

By inserting Eq.(5) to Eq.(3) the following relationship is obtained between the original carbonation coefficient and the frost interacted carbonation coefficient with time.

$$k_{ca;IntFr} = k_{ca0} \cdot \left(1 + 0.21 \cdot \left(\frac{t}{t_{L;IntFr}}\right)^{1.32}\right) \qquad (6)$$

Considering further that the predicted initiation time of corrosion with respect to chloride

penetration without the effect of frost attack is $t_{0;ca}$ the coefficient of carbonation can be written as follows:

$$k_{ca0} = \frac{C}{\sqrt{t_{0;ca}}} \tag{7}$$

where

$t_{0;ca}$ original predicted initiation time of corrosion with respect to chloride penetration,

C concrete cover, mm.

The interaction coefficients for the effect of internal frost attack on the initiation time of corrosion with regard to carbonation ($I_{ca;IntFr}$) are presented in Table 1. The interaction coefficients are tabulated with the original initiation time of corrosion, $t_{0;ca}$, and the service life with respect to internal frost attack, $t_{L;IntFr}$, as they are assumed to be determined first in the process of service life evaluation. Concrete cover is not a relevant parameter in this case. The corrected value of the initiation time of corrosion is determined as follows:

$$t_{0;ca;IntFr} = I_{ca;IntFr} \cdot t_{0;ca} \tag{8}$$

where

$t_{0;ca;IntFr}$ corrected value of the initiation time of corrosion when interacted by internal frost attack (carbonation initiation), years, and,

$I_{ca;IntFr}$ interaction factor for the effect of internal frost attack on the initiation time of corrosion (carbonation initiation).

Table 1 – Interaction coefficients for the effect of internal frost attack on the initiation time of corrosion with regard to carbonation ($I_{ca;IntFr}$)[5].

$t_{0,ca}/t_{L,IntFr}$	20	40	60	80	100	120	140	160
20	0.85	0.90	0.95	0.95	0.95	0.95	0.95	0.95
40	0.73	0.85	0.9	0.93	0.95	0.95	0.95	0.95
60	0.66	0.81	0.86	0.9	0.93	0.95	0.95	0.97
80	0.59	0.75	0.82	0.87	0.90	0.91	0.92	0.94
100	0.55	0.70	0.79	0.84	0.87	0.89	0.91	0.92
120	0.50	0.66	0.75	0.80	0.84	0.87	0.88	0.90
140	0.47	0.63	0.71	0.77	0.81	0.84	0.86	0.88
160	0.44	0.59	0.69	0.75	0.79	0.82	0.85	0.87

CONCLUDING REMARKS

These results presented here give a small example of the wide range of laboratory and field investigations that have been a part of the Finnish project interacted deterioration of concrete. All of the results of this project as well as three earlier Finnish durability projects in cooperation with Aalto University are available on a public database for evaluation and future cooperative studies. The research has shown that single attacks tested in laboratory conditions yield different results than what may actually be experienced in field applications or in-situ concrete structures, where multiple degradation types are occurring simultaneously. The new interacted durability laboratory results have been combined with field studies to improve durability models and service life

prediction tools. The results from this project have had an impact on Finnish concrete practice and durability guidelines.

The future aim is to continue with field testing at the three Finnish sites for at least 20 years, obtaining long term results for calibration and verification of durability and service life models. Another goal is to continue with more comprehensive studies on the interacted deterioration, including also the effects of concrete surface layer properties and ageing on the service life especially with new ecological binding materials.

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REFERENCES

1. Sistonen, E. & Vesikari, E. “Effect of Interacted Deterioration Parameters on Service Life of Concrete Structures in Cold Environments – State of the Art”. VTT Research Report, VTTR0921708. 2008. 42 p.
2. Kuosa, H. ”Concrete durability field testing. Field and laboratory results 2007 – 2010 in DuraInt –project“. VTT Research Report, VTT-R-00482-11. 2011. 93 p. + App.
3. Leivo, M., Sistonen, E., Al-Neshawy, F., Piironen, J., Kuosa, H., Holt, E. & Nordqvist, S. “Effect of interacted deterioration parameters on service life of concrete structures in cold environments. Laboratory test results 2009 – 2011”. VTT Research Report, VTT-R-00482-11. 2011.
4. Kari, O.-P. “DuraInt Report – Task 4 - Deterioration Models with Interaction”. Aalto university research report.
5. Vesikari, E. & Ferreira, R.M. “Frost Deterioration Process and Interaction with Carbonation and Chloride Penetration – Analysis and Modelling of Test Results”. VTT Research report, VTT-R-02782-11. 2011, 42 p.
6. Kuosa, H. “Concrete Durability Field Testing in Finland”. Proceedings of Nordic Concrete Research NCR 2011, Finland, June 2011, p. 247 – 250.
7. Vesikari, E. “Modeling of Carbonation and Chloride Penetration Interacted by Frost Damage in Concrete”. Proceedings of Nordic Concrete Research NCR 2011, Finland, June 2011, p. 255 – 258.
8. Holt E. & Leivo, M. “Concrete Durability Based on Coupled Laboratory Deterioration by Frost, Carbonation and Chloride.” Proceedings of Nordic Concrete Research NCR 2011, Finland, June 2011 p. 239- 242.
9. NT Build 492. “Concrete, mortar and cement-based materials: Chloride migration coefficient from non-steady-state migration experiments”. 1999, 8 p.
10. CEN/TR 15177. “Testing the freeze-thaw resistance of concrete. Internal structural damage”. April 2006, 34 p.
11. CEN/TS 12390-9. “Testing hardened concrete. Part 9: Freeze-thaw resistance. Scaling”. May 2006, 24 p.
12. EN 13295. “Products and systems for the protection and repair of concrete structures. Test methods. Determination of resistance to carbonation”. May 2004, 15 p.