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Chloride Ingress in Concrete with Different Age at Time of First Chloride Exposure



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ABSTRACT

Concrete structures cast in spring have longer time to hydrate and are therefore denser and more resistant to chloride ingress when first subjected to deicing salts in winter than structures cast in autumn. Consequently, it is expected that a spring casting will have a longer service life.

This hypothesis is investigated in the present study by testing drilled cores from concrete cast in 2012 and 2013 on the Svendborgsund Bridge. The cores are subject to petrographic examination and mapping of chloride profiles. Moreover, chloride migration coefficients have been measured. The study shows that the effect of the extra time of hydration obtained when casting in spring increases the expected service life of the concrete structure significantly.

Key words: Chloride ingress, age-dependent chloride diffusion coefficient, field exposure, service life.

1. INTRODUCTION

Chloride ingress can lead to reinforcement corrosion, so for reinforced concrete structures exposed to seawater or deicing salts, the extent of chloride ingress often determines the structure's service life [1]. The resistance against chloride ingress mainly depends on four things: the constituents and mixing proportions of the concrete and the curing conditions and the age of the concrete, as the denseness of the concrete is developed over time [2].

Considering that the age plays a role in the transport properties of the concrete, it seems reasonable to assume that the age of the concrete at first exposure to chloride will play a role in the service life of the concrete. When concrete is relatively young, it will be more permeable, and therefore more chloride will enter into the concrete. Due to concentration differences, this chloride will keep moving into the concrete in the coming years, though the concrete at this stage has become more resistant to chloride transport.

It is the objective of this study to investigate the importance of the age at first chloride exposure for concrete that will be exposed to chloride throughout its service life. The study is conducted as a field study of chloride ingress on the Svendborgsund Bridge. The bridge underwent major repair in 2012 and 2013, and at the same time, the bridge got two new bike lanes. These are made of concrete without asphalt cover, so the concrete is directly exposed to de-icing salts during wintertime. The de-icing salt is the main source of chlorides. The chloride load from airborne chlorides is low due to the height of the bridge and the low salinity of the sea water. Both in 2012 and 2013, repair works started in spring and ended in autumn. Because of this, parts of the concrete were cast in spring and part of it in autumn, and as a result, there are concrete with very different ages at first exposure to chloride from de-icing salts. This offers a unique insight into the importance of concrete age at first chloride exposure.

The Svendborgsund Bridge

The Svendborgsund Bridge was opened in 1966. It leads road traffic over Svendborg Sound, thereby connecting the two Danish islands Fyn and Tåsinge. The bridge is 1220 m long, and it has a ship passing height of 33 meters. On average, 16,000 cars pass the bridge every day [3].

2. THEORY

Concrete is a porous material, and concentration differences of ions will seek equilibrium by gradually diffusing through the pore solution. This includes chloride ions present at the surface of a concrete structure, e.g. as a result of deicing salt or because the structure is placed in marine environment. If the concentration of chloride ions in the concrete is too high, it can lead to corrosion of the reinforcement. The diffusion of chloride ions for a non-steady state situation in a saturated concrete can be described using Fick's 2nd law. The error-function solution to Fick's 2nd law can be used to calculate the chloride concentration to any point and at any time, see Equation (1).

$$C(x, t) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x}{2\sqrt{D \cdot t}}\right), \quad (1)$$

Where

$C(x, t)$ concentration at depth x and time t [%],
 t time of exposure [s],
 x depth from free surface [m],
 C_s surface concentration [%],
 C_i initial concentration [%], and
 D diffusion coefficient $\left[\frac{m^2}{s}\right]$.

The design of the concrete recipe influences the diffusion coefficient significantly, as a denser concrete will yield a lower diffusion coefficient. The w/c ratio is one of the most influential parameters as a large w/c ratio leads to a more porous concrete. Earlier studies have shown that when the w/c ratio varies from 0.2 to 0.7 the diffusion coefficient varies with a factor of almost 50 [4]. The diffusion coefficient also decreases when the maturity increases, as concrete hardening is a continuous process making the concrete denser over time. According to Tang and Gulikers [5], the time dependency was first modeled by Takewake and Mastumoto [6] in 1988, and today there are a number of mathematical approaches to describe the time-dependent diffusion coefficient.

Apart from the parameters stated in Fick's 2nd law, other things may influence the chloride ingress. If the concrete is periodically dried out, the chloride ingress is not pure diffusion, as is the premise for Fick's 2nd law, as in this case also capillary suction can lead to chloride ingress. However, it seems generally accepted that the application of Fick's 2nd law is still useable to extrapolate the future chloride ingress and concentration [7, 8]. In other exposure situations than a pure diffusion situation, the measured diffusion coefficient is an apparent diffusion coefficient. In the following text, no distinction is made between "diffusion coefficient" and "apparent diffusion coefficient".

When determining the service life of a structure in relation to the chloride concentration in the concrete, a threshold must be set for the initiation of corrosion. An often-used value is 0.05% by weight of the concrete [9].

3. MATERIALS AND METHODS

3.1 Materials

The concrete specimens are cores taken from the structure using vertical drilling on the bicycle tracks. The cores are taken at four locations, which are assumed to have the same chloride load (same rain intensity, same dosage of de-icing salts, same distance to car lane, etc.).

The concrete composition stated in the as-built documentation is specified in Table 1. The cement used is a cement in class CEM I 42.5 N. All aggregates fulfill the demands for Danish exposure class E (i.e. XD3/XS3 and XF4 according to EN 206). The coarse aggregates are granite. The water/binder ratio is 0.33. The concrete is air entrained, but the actual air void structure is not documented in the as-built documentation. It is assumed that the air void structure fulfilled the requirements for XF4 at time of erection (minimum air content in hardened concrete 3.5%, maximum spacing factor 0.20 mm).

Table 1 - As built concrete recipe

Composition	Density [kg/m ³]	Amount [kg/m ³]	Volume [l/m ³]
Cement	3200	420.0	131
Fly ash	2300	54.6	24
Water	1000	156.5	156
Air entrainment	1010	0.8	1
Plasticizer	1160	2.8	2
Super Plasticizer	1050	1.2	1
Sand 0-4mm	2630	563.2	214
Coarse aggregates 4-8mm	2680	164.8	62
Coarse aggregates 8-16mm	2680	384.6	144
Coarse aggregates 16-25mm	2680	549.4	205
Aimed air content 6% of volume	-	-	60
Total		2298	1000

In Table 2, it is specified at which age each core was first exposed to chloride, and for how long it has been exposed.

Table 2 - Concrete specimen names, age at exposure, and total time of exposure

Specimen ID	Casting date	Age at first exposure [days]	Total time of exposure* [days]
S12	24-05-2012	155	879
A12	08-10-2012	18	879
S13	10-04-2013	192	521
A13	03-09-2013	46	521

* "Total time of exposure" is the time from first chloride exposure and until the core is drilled. It is assumed that chloride already in the concrete will ingress inwards in the concrete, also during periods, where the concrete surface is not exposed to chloride.

The same concrete cores are used for all tests. The tests are performed in the following order:

1. The cores are examined in the petrographic analysis (section 3.2)
2. The uneven bottom part of each cylinder is cut off and a 50 mm cylinder piece is cut of the bottom. This piece is used to measure the chloride migration coefficient (section 3.3).
3. Thin layers are grinded of the top part of the cylinder and used to measure the actual chloride ingress (section 3.4).

There are two cores from each location, i.e. a total of eight cores. All cores are subject to petrographic examination (1) and migration test (2). The chloride profile (3) is only registered for one core from each location, except for S12 where the chloride profile is registered for both cores to document the variation within a specific location.

3.2 Petrographic analysis

The drilled cores are subjected to petrographic analysis on macroscopic level to ensure that the chloride penetration measurements, as well as the migration coefficient measurements are performed on comparable concrete cores.

The purpose of the petrographic analysis is to determine the quality and condition of the drilled concrete cores as well as determine the differences between them. The petrographic analysis has been performed according to ASTM C856-14 [10] but limited to the following parameters:

- The dimensions of the drilled core, (diameter and height) are measured with a caliper.
- The maximum aggregate size is measured on the surface of the drilled cores with a caliper.
- A visual evaluation on the distribution of the larger aggregates is performed.
- An approximate coarse aggregate percentage evaluation is made. This is performed by placing a ruler along the drilled cores three places and noting for each centimetre mark whether it is pasta phase or aggregates. If a centimetre mark hits a reinforcement bar, the measurement point is excluded. The aggregate percentage is then calculated as the number of points noted in aggregates divided by the total number of measurement points.
- The cores are inspected for visible signs of alkali silica gel.
- A visual comparison of the colors of the pasta phase between the cores is made.
- A visual assessment of mixed in air as well as air entrapped during casting is made.
- Dimensions of the reinforcement are measured (if present in a core).
- Thickness of the concrete cover layer is measured (if reinforcement is present).
- A visual assessment of the fracture surface from when the core has been removed from the structure is made.
- A visual assessment of the texture of the top surface of the cores is performed.
- Additional observations are noted, including indications of the following: separation in the concrete, casting joints, honeycomb and cracks in the core or other features that could indicate poor quality concrete or casting.
- After the bottom part of the cores are cut off for chloride migration test (see section 3.3) the remaining parts of the test specimens are cut parallel to the drilling direction of the test specimens. A slice is cut with a thickness of about 1-2 cm using a diamond circular saw. The slice is cut from the edge of the test specimen to leave as much specimen for chloride profile test as possible (see section 3.4). It is evaluated whether the carbonation have occurred in any of the drilled cores, by checking for color change. If the concrete turns pink, when phenolphthalein is applied, no carbonation has occurred. If the concrete does not change color, when phenolphthalein is applied, carbonation has occurred.

The petrographic examination described above is performed on the intact cores. In addition, the carbonation depth is measured on saw cut slices of the cores, by spraying the slices with phenolphthalein.

3.3 Chloride migration coefficient

It is interesting to investigate whether the test specimens have comparable transport properties by determining their migration coefficients. Natural diffusion is a slow process, and it will take place while the diffusion coefficient is varying, so the diffusion coefficient derived from a

measured chloride profile from natural exposure does not represent the diffusion coefficient at the exact time of testing. Instead a migration test can be performed. This is a relatively quick test, as it only takes a few days to perform, and therefore it provides a better basis for comparing transport properties at a certain age.

In a migration test a section of the concrete core is exposed to one-directional transport of chloride under the influence of an external electrical field. The difference in electrical potential accelerates the diffusion of the Cl^- ions. The test is created to estimate the migration coefficient as close as possible to the diffusion coefficient of saturated concrete at the same temperature. In the rest of the article, the diffusion coefficient determined by migration is denoted as migration coefficient.

In the present study, the chloride migration coefficient is performed according to NT BUILD 492 [11]. The purpose of the method is to determine a non-steady-state migration coefficient for chloride ingress in drilled concrete cores. The principle of the method is to force chloride through a section of a drilled concrete core by applying an electrical potential across the specimen. After a set period, the test specimen is split axially and a silver nitrate solution is applied to one of the split sections. In areas with chloride, white silver chloride precipitation is formed. The chloride penetration depth is measured as the distance from the surface exposed to chloride to the borderline, where the color changes. The measured penetration depth is then used to calculate the non-steady-state chloride migration coefficient.

3.4 Chloride ingress due to field exposure

The rate of the chloride ingress as stated is depending on several parameters whereof the diffusion coefficient is the most predominant variable in specimens tested, as they are assumed to have experienced the same external conditions during exposure.

The method used in this study to produce a chloride profile closely resembles that of the standards NT BUILD 208 [12] and NT BUILD 443 [13] but instead of Volhard titration, a potentiometric titration is used, as this is the standard procedure at DTU Civil Engineering laboratory. To investigate how the distribution of the aggregates affects the chloride profile, a small sample is removed from each layer and the calcium content in the layer is determined via ICP (Inductively Coupled Plasma mass spectrometry). The chlorides can only penetrate the pasta phase which is the only component in the concrete that contains calcium. The chloride content of the concrete can be normalized in relation to the paste content in each layer.

The method is summarized in the following description:

- A drilled core is fixed in a grinding machine, exposed side up, making it possible to grind off thin layers of concrete dust at a time. Extra care is taken to make sure that the top surface of the core is level, so that the layers taken off are parallel with the exposed surface.
- The precise height of the core is noted using a digital caliper, to make it possible to determine the exact thickness of the layers ground off.
- A layer is ground off, and the dust produced is collected, the new height is noted.
- This process is repeated until it is estimated that chloride-ingress depth is reached.
- The sample is turned upside down, and a sample from the bottom is taken, to provide a sample for measuring the initial chloride concentration.

- The dust is chemically dissolved using nitric acid freeing the Cl⁻ ions.
- A small sample is removed for calcium analysis via ICP.
- 1 ml of 0.1 N NaCl solution is added to the sample for titration to ensure titration precision.
- The prepared sample is titrated using silver nitrate to find the chloride concentration.
- A chloride concentration profile is made from the measured depths and the amount of silver nitrate added.
- The exposure time is set to be the time between the concrete's first exposure to frost, as this is likely the first time the road was exposed to deicing salts, and the time when the samples were collected. Data from the Danish Metrological institute's website was used to assess the first day of frost for each of the samples [14]. The chloride concentration from the bottom sample is used as the initial chloride concentration.
- The age of the test specimens at first exposure is shown in table 2.
- The chloride content for each layer is determined using the error function solution to Fick's 2nd law. The measuring point closest to the surface is excluded, as described in NT BUILD 443.

4. RESULTS

In this section all results from the experiments are presented along with the initial conditions for the experiments.

4.1 Petrographic analysis

In the following, the results from the different steps in the petrographic analysis are listed.

Aggregates

- The maximum observed aggregate in the cores, is between 16-27 mm in diameter.
- The aggregate can be considered evenly distributed.
- The coarse aggregate content measured in each specimen varies from 28-41% of the surface area, corresponding to an equal amount by volume, which only includes visible aggregates and therefore does not take small aggregates like sand into account. The prescribed coarse aggregate content is 47% by weight, and about 40% by volume, assuming an aggregate density of 2750 kg/m³ for granite. The measured coarse aggregate content seems to correspond well to the prescribed volume.
- There are no visible signs of alkali-silica reactions. Furthermore, the coarse aggregates seem to be granite based.

Paste

It is assessed that the colors of pasta phase are comparable and no soft spots are found on the surface of any of the drilled cores.

Air void structure

The concrete is air-entrained, and the air voids are well distributed. There are a few entrapments of air.

Reinforcement

The assessed dimension of the reinforcement bars found in the cores are 12 and 17 mm. Reinforcement are not usually sold in 17 mm why it is assessed that the full diameter is larger than 17 mm, possibly 20 mm. The concrete cover layer is registered to 55 mm for the 17 mm reinforcement bars and 75mm for the 12mm reinforcement bars.

Carbonation

Phenolphthalein solution was applied to make the carbonation front visible. The carbonation depth was in all cases lower than 1 mm.

Additional observations

- The fractured surfaces in the bottom of the drilled cores are similar with fracture occurring both through aggregates and pasta phase, which indicates that the pasta phase have a high strength.
- On several cores a different concrete type are observed in the bottom of the core, indicating that the bike lanes are casted on top of an existing structure. The condition of the concrete of the existing structure has not been evaluated.

From this, it can be concluded that all of the concrete samples are sound and meet the specifications for the concrete, and they therefore appear to be comparable.

4.2 Chloride migration coefficient

The results of the chloride migration test are presented in Figure 1.

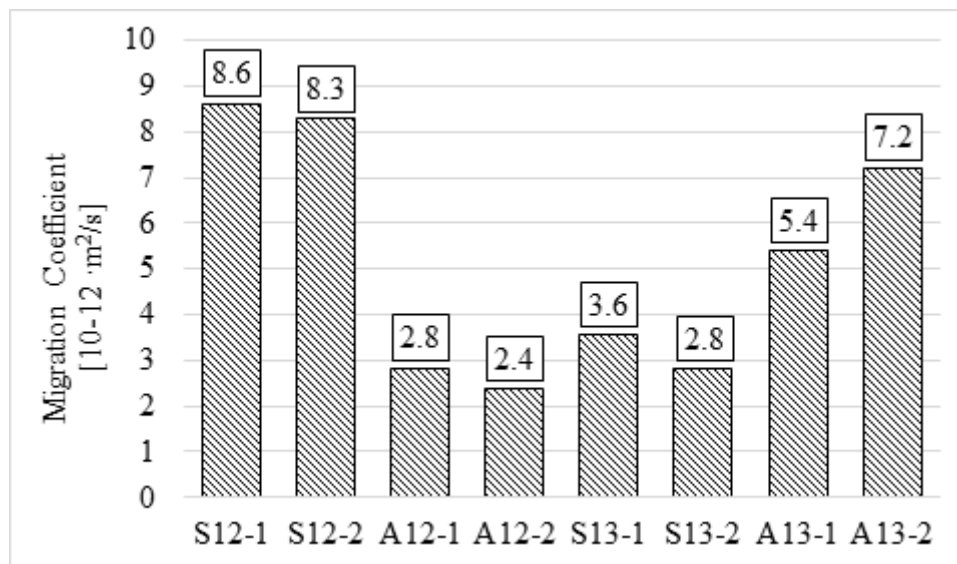


Figure 1 – Migration coefficients

4.3. Chloride ingress due to field exposure

Of the eight drilled cores studied in this paper, a chloride profile analysis is made for five of them, one from each set of cores and both from one set, to document the variation within a specific location. The results can be seen in Figure 2. An average of the initial concentrations, found from analysing the bottom of the sample, is plotted along the bottom of the graph.

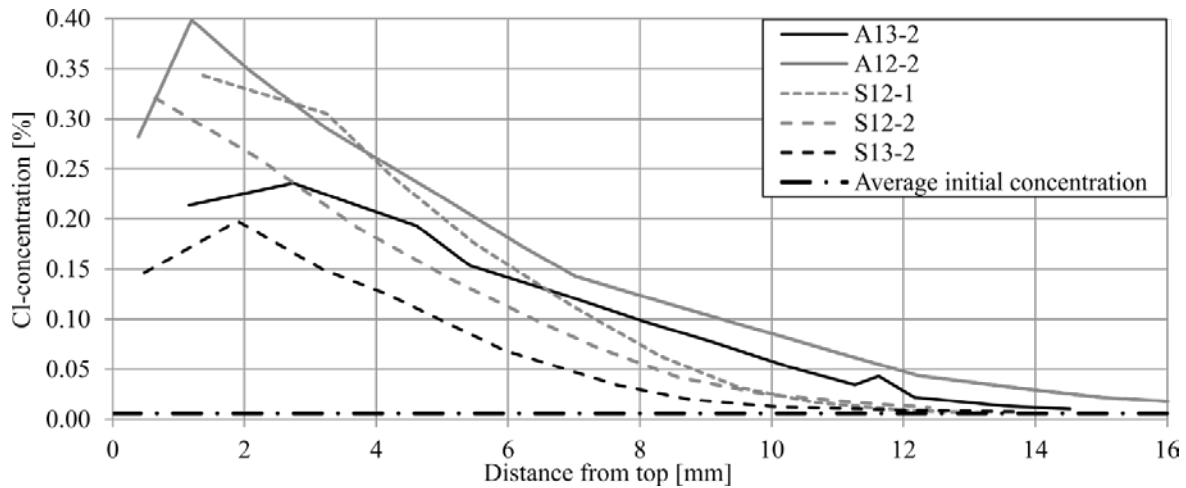


Figure 2 - Comparison of the different chloride ingress profiles

Using the error function solution for Fick's 2nd law, the diffusion coefficient D and the surface concentration C_s are found for each sample. The measuring point closest to the surface is not used in the curve fit. This is according to practice in [13]. For most of the profiles, the chloride concentration measured closest to the surface is lower than the concentration measured in the second closest point. This is not physically meaningful according to Equation (1). C_i is set to be equal to the concentration found in the bottom of the sample. The error function solution is plotted as a curve next to the measured data in Figure 3.

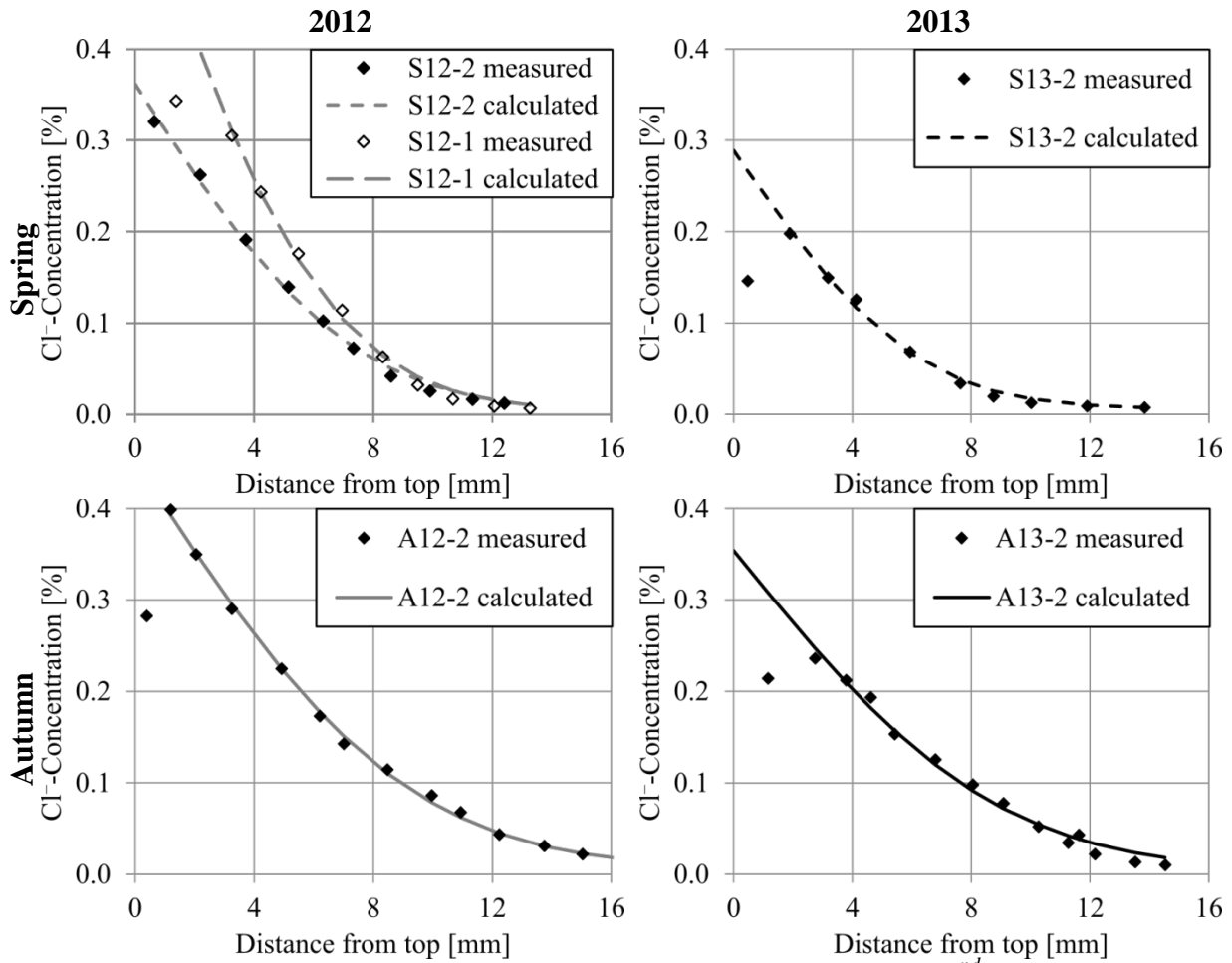


Figure 3 - Measured compared to calculated concentrations using Fick's 2nd law

The concentrations in the points closest to the surface can be misleading, so even though all of the data is displayed, only the point matching a diffusion curve with decreasing concentrations as the distance to the surface increases are used to determine the diffusion coefficient by curve fitting.

As mentioned earlier a sample was taken from each layer to measure the calcium concentration. The results of this can be seen on Figure 4.

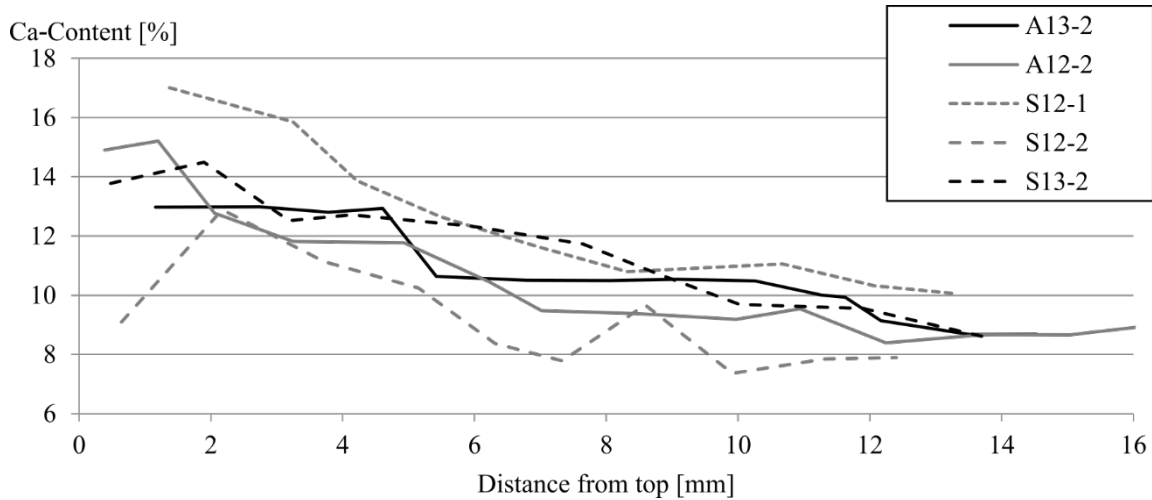


Figure 4 - Ca-concentrations

The concentration is higher in the surface layer of the sample due to uneven distribution of cement paste. The calcium concentration evens out at depth 10-12 mm, corresponding to approximately half the maximum aggregate size. The calcium concentration profiles can be used to correct errors in the chloride profile.

5. DISCUSSION

5.1 Petrographic examination

Based on the observations made during the petrographic analysis of the drilled cores it is concluded that the execution of the concrete works are of high quality and consistent. The amount of entrapped air is larger in the castings performed in 2013 compared to the castings made in 2012. However, the amount of air entrappings along with the distribution is assessed not to influence the quality of the final durability of the concrete significantly. The concrete is air entrained and there are no signs of damage that can be related to frost action. The carbonation is hardly noticeable in the drilled concrete cores.

5.2 Chloride migration coefficient

The results in Figure 1 show that the migration coefficients for samples from the same location are on the same level. According to the test method [11], the coefficient of variation of repeatability is 9%. For some of the locations, the difference between two measurements surpasses 9%, but that is because the specimens are not fully identical.

Migration coefficients between different locations vary. The largest migration coefficient is 3.6 times larger than the smallest migration coefficient. This is a significant difference, as the difference is much larger than the accuracy of the test method. There does not seem to be a systematic trend as regards casting season; for samples cast in 2012 the migration coefficient for the spring casting is higher than the migration coefficient for the autumn casting, but in 2013 the results show the opposite. There is no systematic trend as regards the age of the sample either. The highest migration coefficient is registered for the oldest sample, and this was expected to have the lowest migration coefficient. However, the migration coefficient is highly dependent

on the mix composition. In a concrete production (not a laboratory mix) it is likely that the w/c ratio varies up to ± 0.02 from the target w/c ratio of the recipe, and this can explain the differences in migration coefficients.

Moreover, local variations may lead to some uncertainty of the results. Figure 5 shows the split samples from the migration test for two samples from the same location.

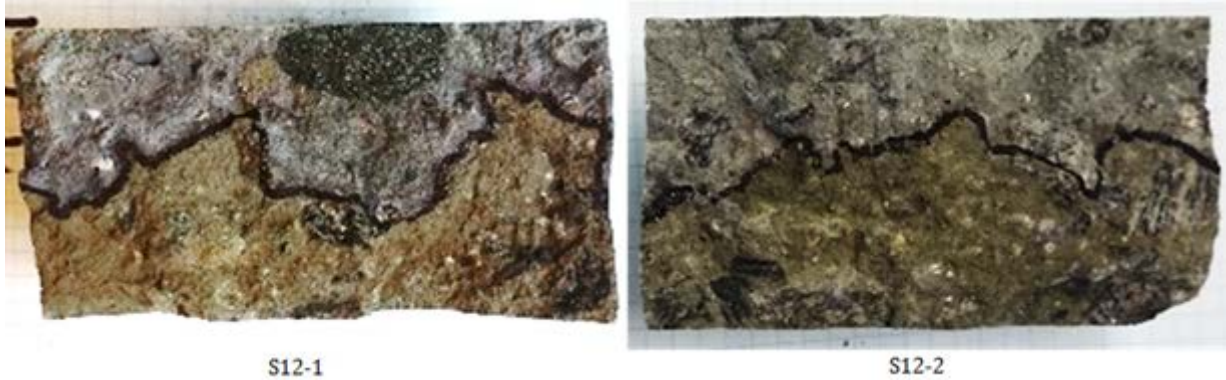


Figure 5 - Chloride migration profiles from accelerated migration coefficient test. The pictures are color adjusted for better contrast

It is observed that even though the migration front of the two samples shown in Figure 5 should be similar, as they are paired samples, it varies a lot. In S12-1 it looks like the chloride have penetrated the specimen much deeper at the dark aggregate that shows up in the figure. This may indicate that the aggregate may have been porous and have accelerated the chloride transport through the aggregate itself. A closer examination of the aggregate indicates that it is not granite like the rest of the aggregates; however a final conclusion on the influence of the aggregate could not be made.

5.3 Chloride ingress due to field exposure

Figure 4 shows that the calcium content (and therefore also the paste content) is highest closest to the surface. The calcium content seems to reach a stable value 10-12 mm from the surface. This equals approximately half of the maximum aggregate size, which is 25 mm.

As mentioned, the chloride concentrations can be corrected with the use of the calcium concentrations. Figure 6 shows the same data as Figure 3, but now the chloride content is normalized to the calcium content. It can be observed that the difference between cores from the same location S12-1 and S12-2 seen in Figure 3 has now disappeared, so the explanation for the difference seems to be differences in paste content. The point closest to the surface still has a lower concentration than the second point. This may be related to the exposure situation, e.g. that chloride in the very surface layer is washed out by rain in the spring.

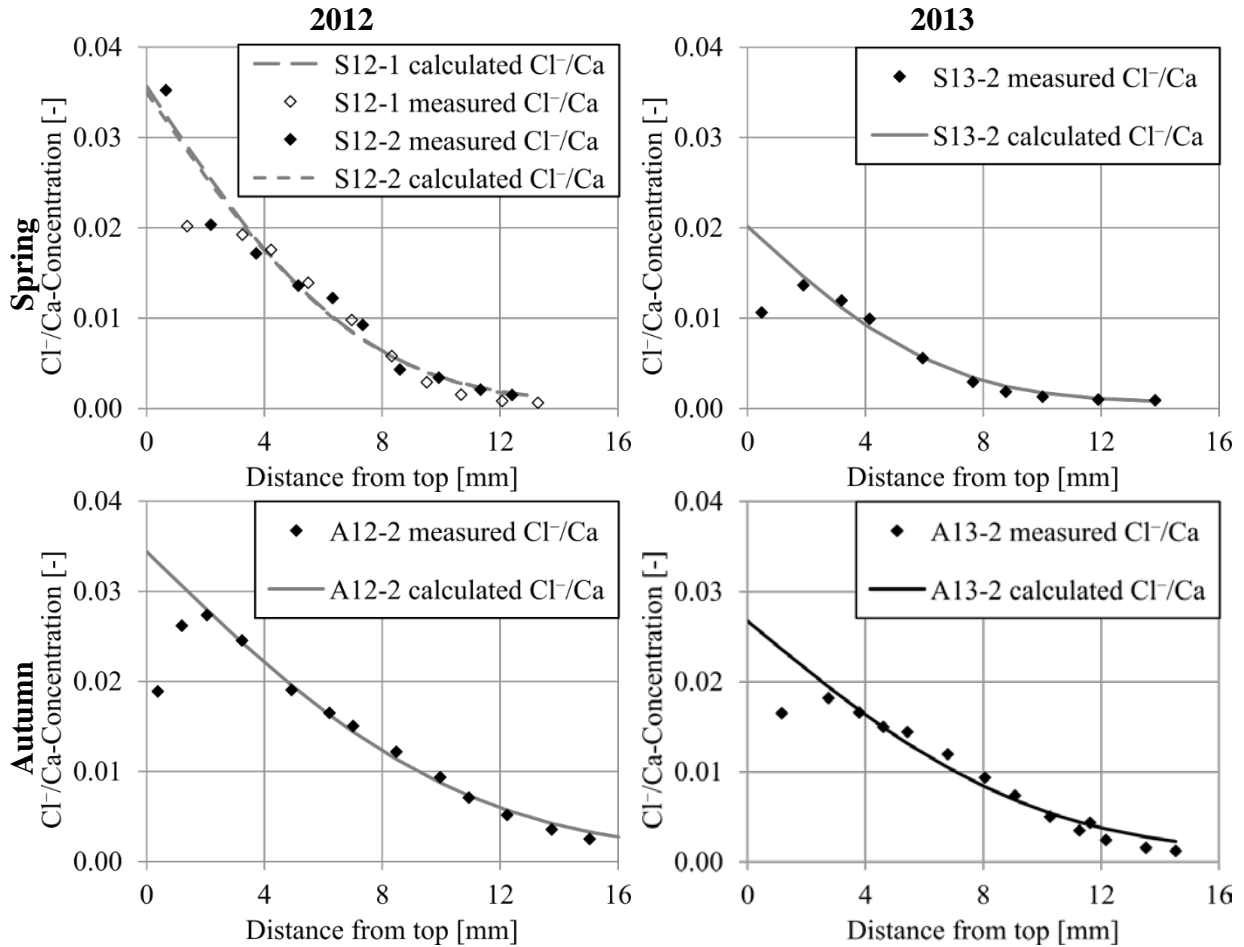


Figure 6 - Measured concentrations compared to concentrations calculated using Fick's 2nd law. Ca-calibrated.

From the calculated profiles shown in Figure 6, the surface concentrations and the diffusion coefficients can be found for Ca-calibrated measurements, as it was done for the un-calibrated measurements in Figure 3. The diffusion coefficients found for the un-calibrated and calibrated measurements are compared in Figure 7. The general trend is that the diffusion coefficient found for Ca-calibrated measurements is higher than the diffusion coefficient found by curve fitting to un-calibrated measurements. This is to be expected, when the paste content is higher near the surface than the average paste content of the bulk concrete. The largest difference is found for A12-2, where the diffusion coefficient is increased 42% by the calcium calibration.

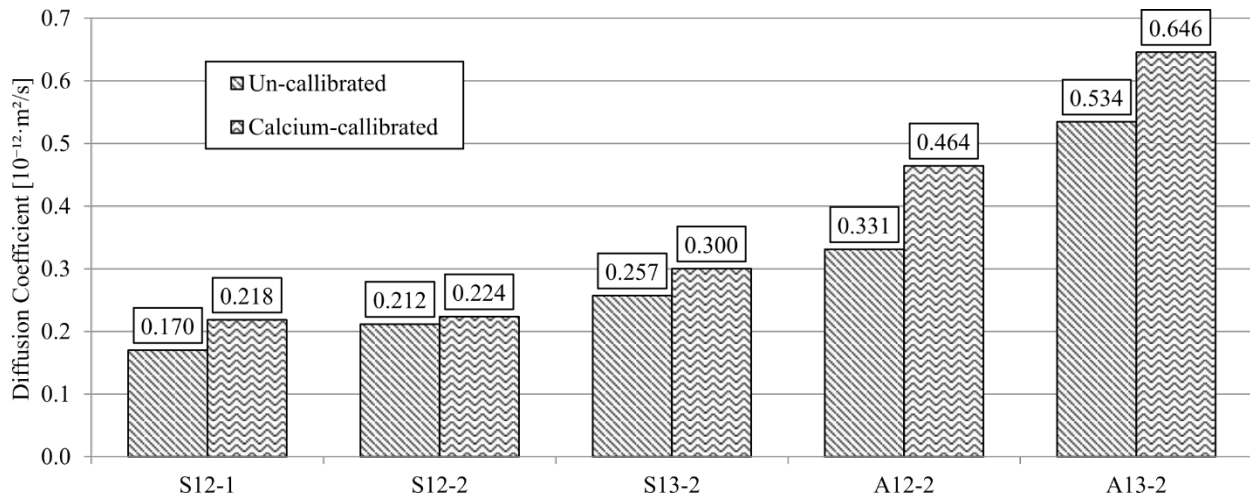


Figure 7 - Comparison of diffusion coefficients.

The calcium-calibration does not change the picture that can be observed in both Figure 3 and Figure 6. In both figures it is observed that the chloride ingress is lower in the cores cast in spring than the ones cast in autumn. Figure 7 shows that the diffusion coefficients are notably higher for the autumn castings than for the spring castings. This conflicts with the results of the migration test. The migration test results show no clear tendency that the autumn cores have a higher diffusion coefficient than the spring cores. If the migration coefficients had shown the same tendency, the results could be contributed to the concrete quality, different curing conditions, etc. Now, the most likely explanation seems to be the chloride ingress at early age in the samples from autumn castings. As stated earlier, the migration coefficient measurement is made over a very short time, where the diffusion coefficient is expected to be constant within the test period. The diffusion coefficient calculated using the chloride ingress profile is a sort of weighted average for the time where the concrete has been exposed to chlorides. Here it can change the result, if the exposure period comprises a period, where the concrete was young and therefore had a high diffusion coefficient.

Furthermore, Figures 3 and 6 show that cores from 2012 have a higher chloride surface concentration than the cores cast in 2013. On one hand, this may be because the surface concentration is gradually building up, and the cores from 2012 have been exposed to three winter seasons compared to the cores from 2013, which have only been exposed to two. On the other hand, it may be because the surface concentration was essentially established in the first winter season, and the winter 2012/2013 gave rise to more heavily use of de-icing salts than the following two winter seasons. It is not possible to determine which of the two explanations that is correct, and it is also possible that they both play a part.

5.4 Effect of casting season on service life

When the ingress parameters C_s , C_i , and D are known, it is in principle possible to predict when the chloride concentration at the reinforcement level reaches a critical level and thereby assess the potential service life. The obtained diffusion coefficients are based on the chloride ingress that have taken place in the first years of the life of the structure, and extrapolation from these data are normally conservative, as the diffusion coefficient will continue to decrease with developing maturity.

The present data shows the difficulties in making a precise service life prediction. It is probably the measured migration coefficients that are best in ranking the transport properties anno 2015 of the concrete castings, i.e. in which casting the chloride transport is fastest and slowest. But the measured migration coefficients cannot be used for prediction of service life, as the test circumstances do not represent the actual exposure conditions. The migration coefficients are at least a factor of ten higher than the diffusion coefficients deduced from the chloride profiles.

If the chloride profiles are extrapolated in time to predict the service life, then the diffusion coefficients of the autumn castings are approximately twice the value of the diffusion coefficients of the spring castings. According to Equation (1), the time needed to reach a certain concentration at reinforcement level will be twice as long for a spring casting, compared to an autumn casting. However, this will overestimate the effect of the casting season, as the factor 2 between diffusion coefficients is not a realistic representation of difference in the transport properties in the long run. There will also be significant differences between the predicted service life based on measurements from castings in 2012 and 2013, due to differences in surface concentrations, i.e. predictions based on measurements for castings in 2013 will result in longer service lives, due to lower surface concentrations. The surface concentrations are expected to become more equal over the years, as the effect of the first winter season exposure will vanish.

Despite the challenges in predicting the service life accurately, it is possible to estimate the effect of the casting season by using the analogy of equivalent cover layer thickness, which can also be used to evaluate the effect of surface coatings [15]. Four test specimens exist, cast in in respectively spring and autumn of two consecutive years. It is assumed that the chloride exposure are identical for each test specimen location within each year, and so two chloride exposure histories exist, one for each year.

The principle is to calculate the difference in the initial chloride ingress by translating the spring data horizontally in the plots in order to calculate the extra cover layer needed to obtain the same service life for an autumn casting as for a spring casting. The calculation is made by including the extra depth needed to fit the chloride profile of the spring test specimens to that of the autumn ones in the solving process along with the surface chloride concentration and the diffusion coefficient.

The fitted results are presented in Figure 8.

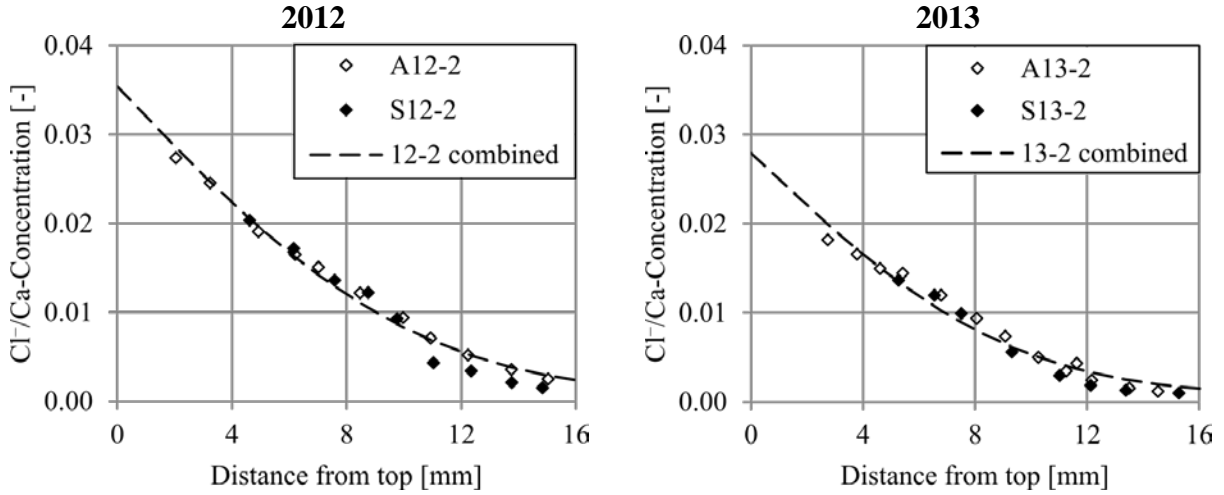


Figure 8 – Calculation for assessment of extra cover layer.

The castings performed in 2012 and 2013 result in differences in concrete cover layer of 2.4 mm and 3.4 mm, respectively.

If the imaginary reduction of the cover layer of the autumn casting is denoted Δx , then the service life of an autumn casting relative to a spring casting can be calculated by rearranging Equation (1) and assuming that the critical chloride concentration will be the same in the two cases, see Equation (2):

$$C(x, t) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x_{cover}}{2 \cdot \sqrt{D \cdot t_{spring}}}\right) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x_{cover} - \Delta x}{2 \cdot \sqrt{D \cdot t_{autumn}}}\right); \quad (2)$$

$$\Rightarrow \frac{x_{cover}}{2 \cdot \sqrt{D \cdot t_{spring}}} = \frac{x_{cover} - \Delta x}{2 \cdot \sqrt{D \cdot t_{autumn}}};$$

$$\Rightarrow t_{autumn} = t_{spring} \cdot \left(\frac{x_{cover} - \Delta x}{x_{cover}}\right)^2.$$

Where

- x_{cover} cover layer thickness [m],
- t_{spring} service life for a spring casting, and
- t_{autumn} service life for an autumn casting.

In Table 3, the reduction in service life for an autumn casting is calculated for two different cover layer thicknesses; 40 mm, which is the minimum allowable cover layer in extra aggressive environment in Denmark [16] and 55 mm, which was the minimum cover layer registered in the cores from Svendborgsund Bridge.

Table 3 – Reduction in service life for an autumn casting, given different assumptions

		Cover layer	
		40 mm	55mm
Cover layer	2.4 mm (2012)	12 %	9 %
reduction Δx	3.4 mm (2013)	16 %	12 %

As can be seen in Equation (2), the calculation in reduction of service life is independent of the assumed critical chloride concentration. The calculation can also be performed, without estimating the service life for a spring and autumn casting, respectively.

6. CONCLUSION

It is concluded, based on the chloride ingress measurements from the field exposed test specimens, that the age at which concrete is subjected to chloride for the first time has a significant influence on the chloride ingress in the structure. When concrete is exposed to chlorides at an early age the resulting higher diffusion coefficient of the concrete will result in deeper and faster chloride ingress in the structure. This results in earlier initiation of corrosion of the steel reinforcement, and therefore a shorter service life. How much the service life is reduced, depends on the total cover layer thickness. For the field exposed cores investigated in this study, where the cover layer is 55 mm, the expected service life is calculated to be 9-12 % shorter when the concrete is cast in the autumn compared to when the concrete is cast in the spring. If the cover layer had been only 40 mm, the reduction in service life would be 12-16 %. This knowledge should be taken into account when planning future concrete structures with risk of chloride exposure.

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