

**DETERIORATION MODELLING
MODEL VERIFICATION THROUGH IN-SITU TESTS
GREAT BELT LINK TUNNEL (DENMARK)**

Carola K. Edvardsen
COWI A/S, Denmark

ABSTRACT

Moisture and chloride conditions of submerged concrete structures are not easy to predict. Knowledge on moisture flow and chloride penetration properties of submerged concrete structures is still lacking to a large extent. The hereby presented in-situ investigations of concrete from the submerged Great Belt Link Tunnel in Denmark may be the first attempt to fill this gap.

1. INTRODUCTION

The moisture and chloride conditions of a concrete structure have a decisive effect on many parts of deterioration processes and, consequently, have a significant effect on the durability of a structure.

The moisture condition of indoor concrete is fairly well-known and possible to predict. Information about the conditions of outdoor concrete structures is scarce, especially properties and conditions of concrete structures exposed to long-term, constant water pressure such as submerged tunnels are much less known and studied to a very small extent. In tunnel structures submerged in seawater the moisture plays an even more active role when salts are penetrating the concrete when moving with the water and depositing where and when the moisture evaporates. In addition, actual data on chloride accumulation on the inside surface of tunnels in case of leaking cracks, joints and other leaking inserts are lacking.

This study was part of Workpackage 2 “Service Life Aspects” of the DARTS project where cores from the Great Belt Link Tunnel in Denmark have been extracted to define the moisture and chloride transport conditions of existing tunnels. Based on this information, a more reliable assessment and maybe even a more reliable calculation of the risk of chloride induced reinforcement corrosion in tunnels exposed to salt containing water (seawater, brackish water, and groundwater) will be possible in the future.

2. BACKGROUND

2.1 Moisture and chloride transport in concrete

The water and chloride transport to consider at submerged tunnel structures is a complex phenomenon involving moisture transport in the concrete pores due to capillary absorption, water vapour diffusion, superimposed by flow due to hydraulic head, together with chloride ion diffusion, chloride binding and possibly chloride salt precipitation.

Different hypotheses/models describing the moisture and chloride transport mechanics of submerged concrete structures have been presented. Most of these are based on laboratory experiments, and none of these models are deduced from on-site investigations of existing tunnel structures. The hypotheses/models are often controversial, which is, however, not surprising considering the complexity of the phenomenon.

One model is based on investigations performed in 1988 on five Danish swimming pools¹. The moisture and chloride contents of concrete cores extracted from the basin walls have been determined. The water/cement ratios of the concretes were between 0.4 and 0.6, and none of the concrete types contained pozzolans. The investigation indicated that an accumulation of chlorides took place at the air-exposed face (service gallery), causing severe reinforcement corrosion after 10-18 years in operation.

Based on the experience from the swimming pools, a “Danish” model (see Fig. 1) for transport mechanisms in concrete tunnels exposed to saline water was derived.

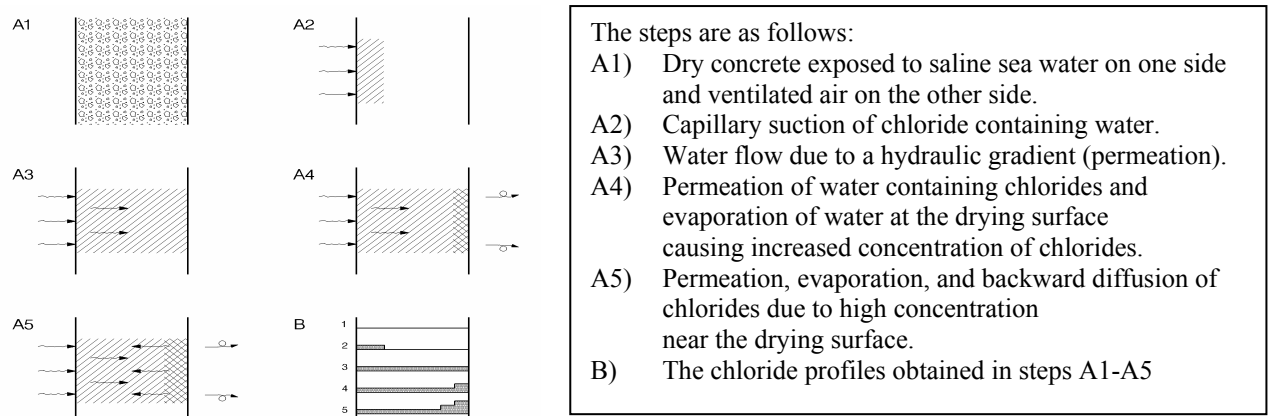


Figure 1 The various steps of moisture and chloride ingress in a tunnel wall or lining with different environmental conditions at the two surfaces¹

The swimming pool investigations made it clear that when evaluating the risk of deterioration, the accumulation of aggressive substances by evaporative effects on the air-exposed face of walls should be considered. Similar environmental conditions exist at submerged tunnel structures where the external walls are exposed to saline water on one side (external surface) and to ventilated air on the other side (inner surface).

The above model is controversial and discussed by leading European concrete and durability experts. Most experts doubt whether a certain water flow and, subsequently, chloride ingress will even occur in modern high performance concrete (HPC), i.e. a less permeable concrete compared to the concrete used for the swimming pools, and in particular for tunnel structures with large thicknesses which could be 700-800 mm for cut & cover walls and typically 300-500 mm for bored tunnel segments.

Experimental studies performed by Beddoe² may confirm the hypothesis that concrete is much more watertight than anticipated so far. Beddoe performed long-term capillary suction tests on concrete with w/c-ratios between 0.40 and 0.75 which include the whole spectrum between modern dense standard concrete and porous sub-standard concrete.

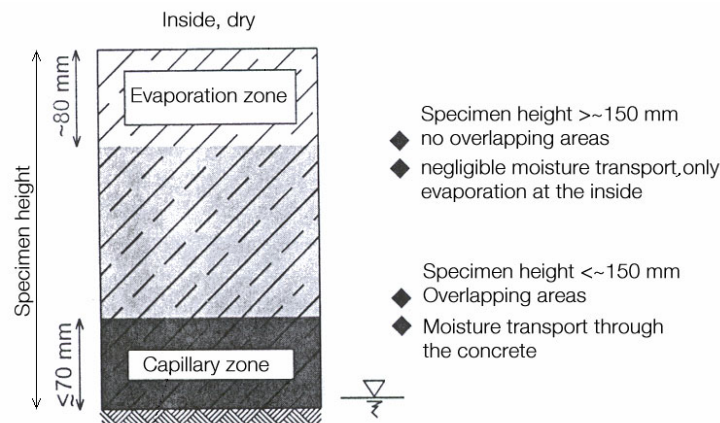


Figure 2 Model for the moisture transport in case of capillary suction for concrete elements²

On the basis of his results, Beddoe developed a model for the moisture transport, (see Fig. 2). The moisture transport in concrete is controlled by an evaporation zone roughly 80 mm deep at the surface and exposed to air, and a capillary zone of up to 70 mm thick at the surface and exposed to water. In case of the concrete thickness being below 150 mm, the two overlapping zones lead to enhanced moisture transport and increased water saturation of the concrete. At thicknesses larger than 150 mm an intermediate zone appears with negligible water transport. The thicknesses of the two border zones - the capillary and the evaporation zone - may depend on the concrete mix, the curing and, to a certain extent, on the temperature.

A Swedish project on durability of marine concrete structures³ included moisture profile measurements on cores extracted from two concrete bridge structures submerged in seawater. A surprising discovery was the low relative humidity (RH) and degree of water saturation (S_{cap}) of concrete submerged in seawater for decades. In one example a 36 year old concrete (specified w/c = 0.60, however, the concrete was very dense and had a strength of some 90 MPa!), continuously submerged in seawater, was saturated only to a depth smaller than 30 mm. Deeper than 30 mm, RH was around 80%, and S_{cap} was 0.75-0.80.

A second example comprised an 18 year old bridge³. In this case the RH was around 100% at the surface of the submerged concrete, but at depths larger than 20 mm the concrete was not saturated. RH was around 85% and S_{cap} was 0.85-0.90 at depths from 40 to 270 mm of the concrete continuously submerged.

The project also included tests measuring the degree of capillary saturation of concrete samples cast for this purpose. It was astonishing, however, that these samples easily absorbed tap water to reach capillary saturation in the laboratory. Whether the original concrete surface absorbed tap water or not was not tested. The conclusion of the project was that the well-known moisture mechanics for indoor concrete did not seem to be applicable for structures exposed to seawater. It seems that the sorption isotherms of exposed concrete are different from unexposed ones. An explanation for this may be that seawater contains magnesium salts, able to densen the concrete surface with layers of brucite. Similar tendencies were observed from laboratory investigations performed by Buenfeld et.al.⁴.

Beside this effect that the water substances may decrease the moisture transport, it seems obvious that the moisture transport mechanisms of porous materials traditionally regarded as being vapour flow and liquid flow have to be reconsidered in case of HPC. For HPC, it seems more reasonable that the pure liquid flow is negligible. The significant portion of transport paths for moisture should be diffusion of moisture through gel, to some extent in series with diffusion in air, depending on the surrounding conditions⁵. This theory implies that the penetration of chlorides in HPC will be extremely slow, since the transport as well takes place as diffusion within the gel pore system.

Another explanation that may explain the discrepancy between the findings in the laboratory and the in-situ observations is related to the dimensions of test samples relative to real structures. It is questionable whether the results derived from relatively thin concrete specimens at short-term water exposure are also valid for meter thick concrete structures.

3. IN-SITU INVESTIGATION

3.1 Tunnel conditions and extracted cores

The Great Belt Tunnel (Denmark), at that stage over 12 years in operation as a railway tunnel, consists of a 7.9 km twin bored tunnel with cut & cover end-sections of 200-250 m and cross passage tunnels per 250 m. The bored tunnel is constructed through varied ground conditions with glacial tills and overlying marl, both strata of a relatively porous nature which allow the full hydrostatic water pressure to act directly on the tunnel lining. The cut & cover tunnel is backfilled with clay material, a full hydrostatic water pressure can be assumed here as well. This means that the water pressure for the bored tunnel varies between 2-7.5 bar, and for the cut & cover tunnel between 1-2 bar. Both types of tunnel are exposed to saltwater (chloride content of the seawater $\sim 1.9\%$ Cl⁻). The concrete mixes of the tunnels are very similar (cement content (bored/cut&cover): 315/335 kg/m³, fly ash: 41/60 kg/m³, micro silica: 21/20 kg/m³, equiv. water/binder ratio: 0.31)⁶. The main differences are that the concrete for the bored tunnel is not air-entrained, the bored tunnel segments are pre-fabricated, whereas the cut & cover tunnel is in-situ cast. These concrete mixes represent HPC.

A total of 12 cores were extracted from the tunnel walls, six from the bored tunnel (B1–B6) and six from the cut & cover tunnel (C1–C6). The location of the 12 cores along the tunnel alignment and the belonging hydrostatic pressure is shown in (Fig. 3). The cores were drilled all the way through the tunnel walls, i.e. over a lining thickness of 400 mm (bored tunnel) and 800 mm (cut & cover tunnel) respectively, against a water pressure of up to several bars. This action demanded special precautions and a special for the purpose constructed coring and grouting equipment, (see Fig. 4 (left)).

Some cores were extracted just beneath a leaking joint or a leaking grout hole or the like (cores B3,B4,B5,B6) and close to a leaking crack (cores C1 and C2, (Fig. 4) (right side)) to obtain additional information on the influence of a presumably locally increased chloride surface accumulation caused by an undesirable high ingress of water at malfunctioning joints, inserts or cracks. The remaining cores (B1,B2 and C3,C4,C5,C6) were taken from a “normal”, i.e. unaffected area with no visible signs of direct contact with seawater. Always, two cores (in a pair of cores) were extracted close to each other as one core was used for the moisture tests and the second one for the chloride investigations.

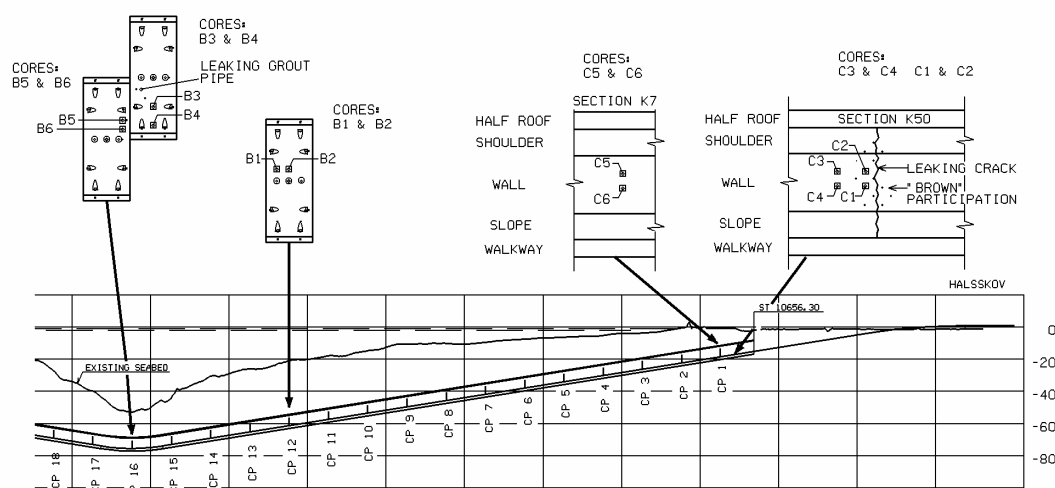


Figure 3 Location of the extracted concrete cores along the tunnel alignment with belonging hydrostatic water pressure

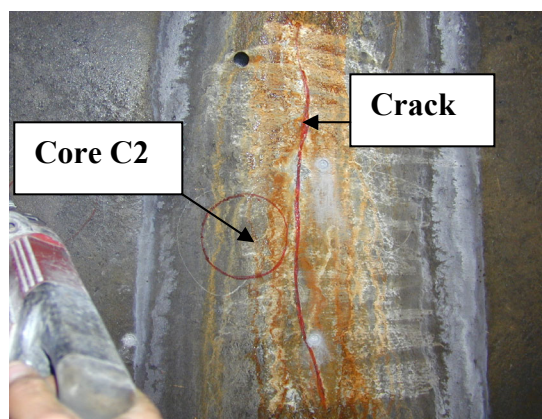


Figure 4 Parts of the purposed made coring equipment used for the extraction of cores under high water pressure (left side) and location of core C2, extraction close to leaking crack (right side) with brown precipitation (ochre) from the water

3.2 Moisture and chloride investigations

The following investigations were performed on the extracted cores:

- Determination of moisture profiles: Several steps, each about 25-30 mm concentrated at the outer surfaces (internal and external tunnel surfaces) and the central part of the cores. Analyses of relative humidity RH, water content U, degree of vacuum saturation S_{vac} (Figure 5).

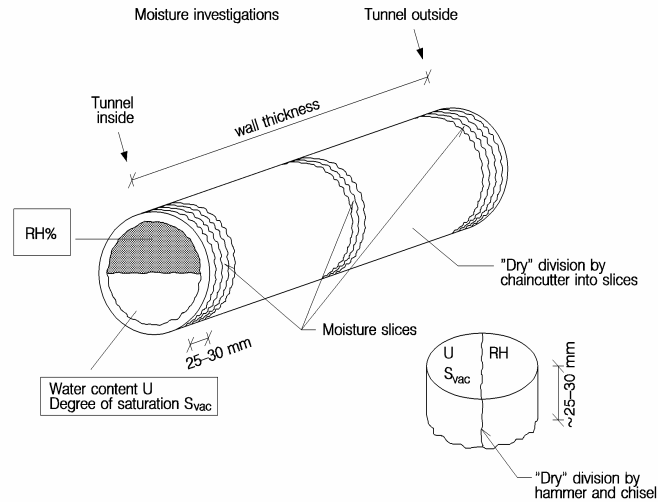


Figure 5 The general principle of fragmentation of the concrete cores used for the moisture investigations

- Determination of chloride profiles: Profile grinding (analysis mm by mm) and chloride analysis concentrated for the outer surfaces and the central part of the cores. From the chloride profiles the apparent diffusion coefficients have been calculated using a non-linear regression analysis of the analytical solution of Fick's second law. For comparison determination of chloride migration coefficients according to NT Build 492 by using concrete sections from the intact middle part of cores since the middle part of the cores turned out to be almost chloride-free, i.e. only loaded with the virgin chloride content.

4. RESULTS AND DISCUSSION

4.1 Moisture

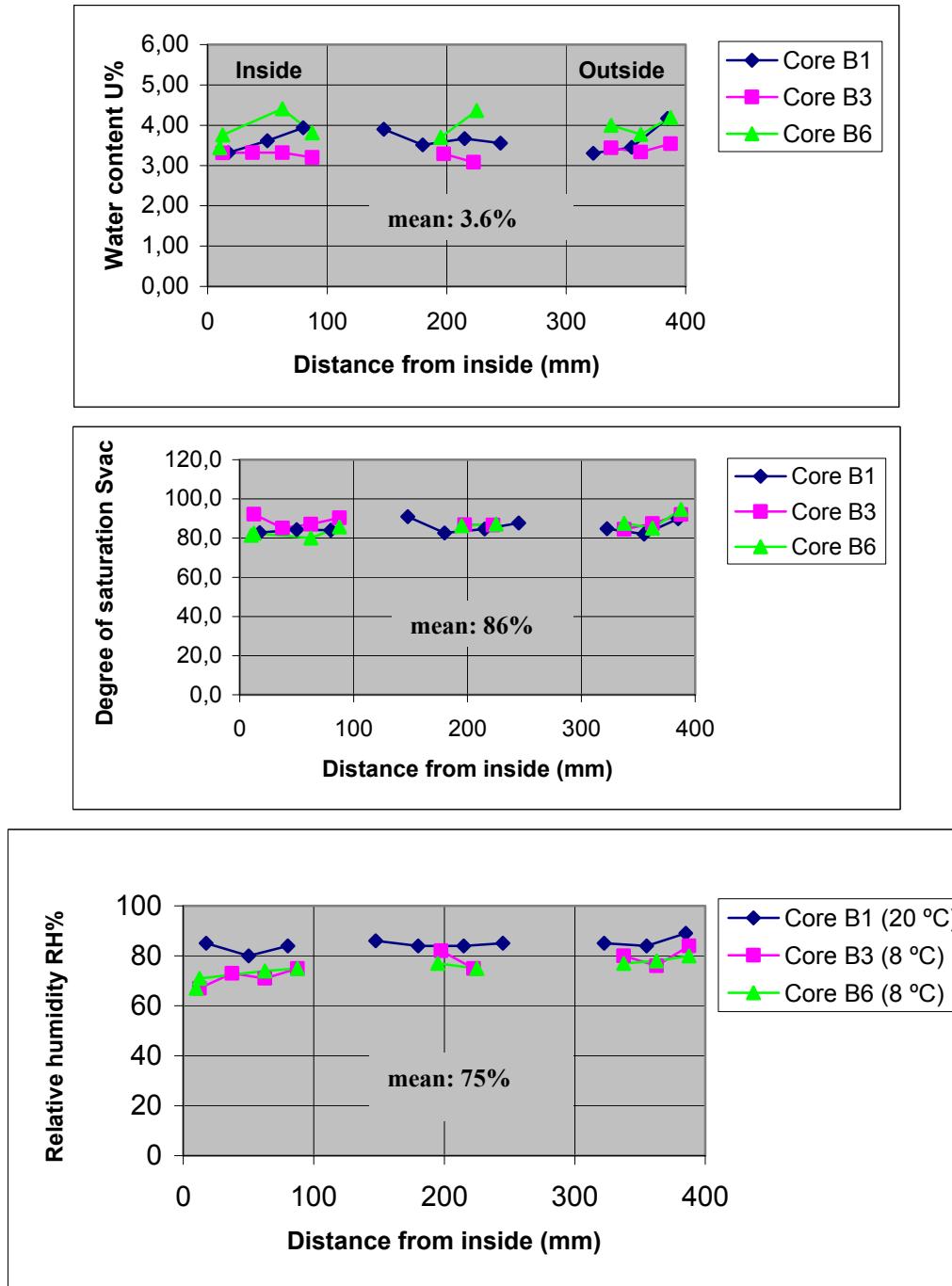


Figure 6 Bored tunnel - water content U , degree of vacuum saturation and relative humidity (at 20 and 8 °C) as determined on the different cores

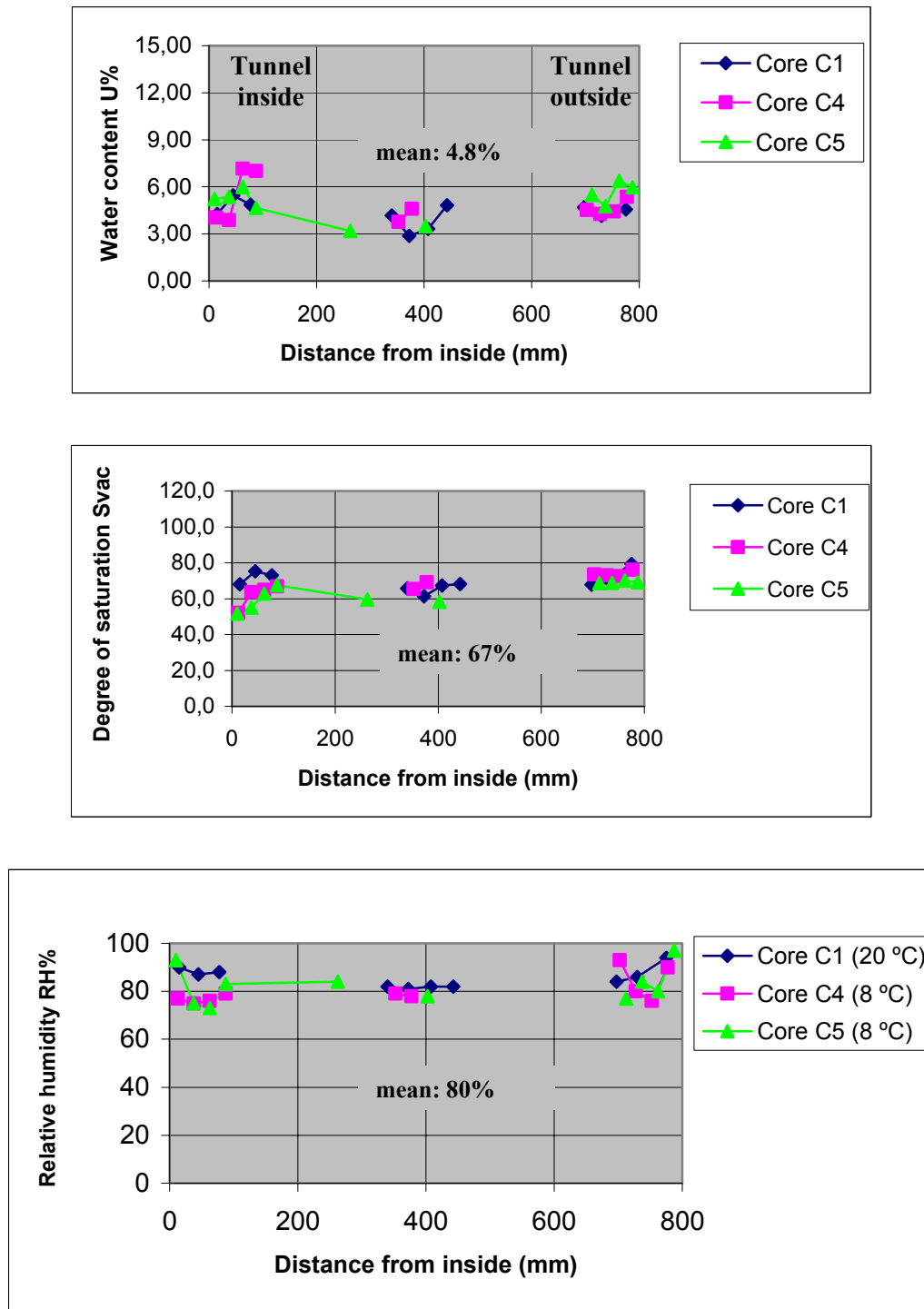


Figure 7 Cut & cover tunnel - water content U , degree of vacuum saturation and relative humidity (at 20 and 8 °C) as determined on the different cores

The following evaluations can be drawn:

- A general tendency is that Inside results are reduced and Outside results increased compared to average values, indicating that water uptake has taken place on the exposed outer surface and drying on the inside (air-side).

- The average results for relative humidity and degree of vacuum saturation are at a level corresponding to a concrete at w/c-ratio 0.3-0.4 that is undergoing self-desiccation, e.g. no exchange of moisture with the surroundings.
- The difference between the degree of vacuum saturation for the concrete from the bored tunnel and the cut & cover concrete is probably explained by 6% air-entrainment in the cut & cover concrete, whereas the bored tunnel concrete is not air entrained (air voids are assumed to be filled with water during vacuum saturation).
- The difference between total moisture content U for the bored tunnel concrete (3.6%) and the cut & cover concrete (4.8%) is not easily explainable as the two concrete types are of similar composition.

4.2 Chlorides

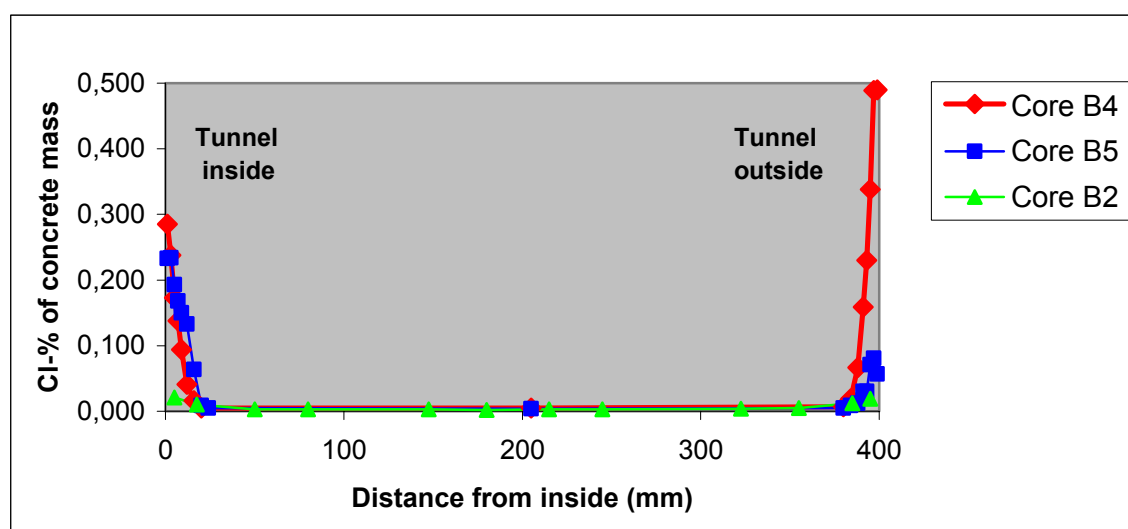


Figure 8 Bored tunnel - Chloride content along the tunnel wall as determined at the different cores

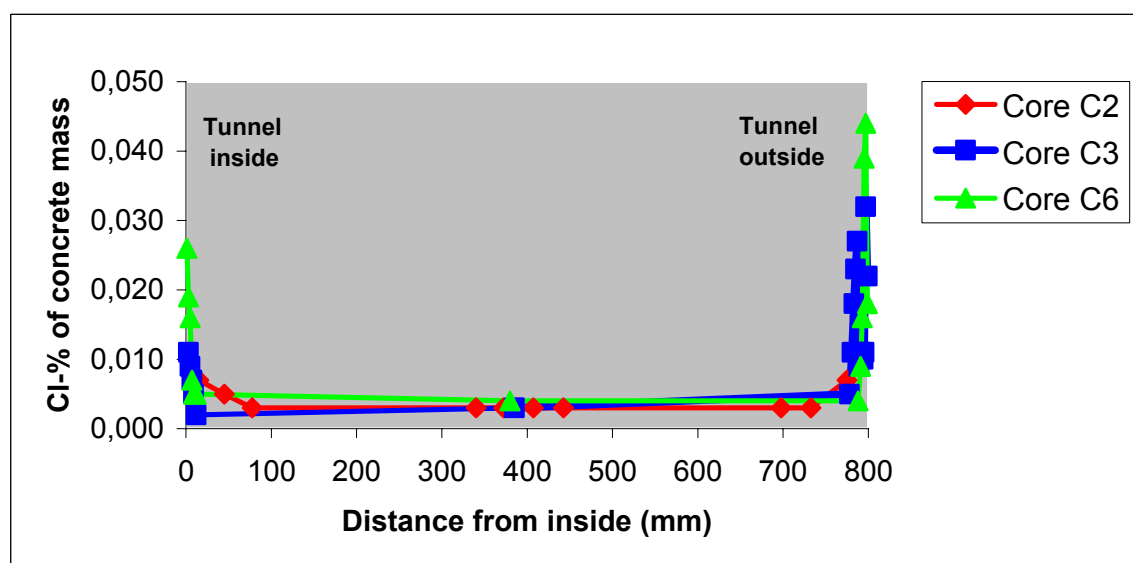


Figure 9 Cut & cover tunnel - chloride content along the tunnel wall as determined on the different cores

The evaluation of the chloride results suffers from the following uncertainties concerning exposure conditions:

- both for the bored tunnel and cut & cover tunnel- the amount of water the concrete on the tunnel outside is actually exposed to is not known.
- the chemical composition of the seawater (bored tunnel) or the combined seawater-/groundwater (cut & cover tunnel) is not known. It is not known whether it is "staying" or "flowing" (i.e. continuous supply of chlorides) water.
- possible exposure and time of exposure of internal concrete surfaces to chloride containing water due to cracks or leakages at joints or inserts.
- possible pre-loading of the concrete with chlorides (in particular the segments which were stored over some time close to the sea and partially sailed over sea to the remote tunnel portal before they were installed in the tunnel).

With the uncertainties in mind the following evaluations may be drawn:

- The results for 4 cores from the 800 mm thick cut & cover tunnel are very similar to each other, showing an increased chloride content near the outermost exposed surface (to approx. 14 mm depth) as well as in the concrete nearest to the inner wall surface (to approx. 10-14 mm depth from the air exposed side). The concrete in between has a very low chloride content corresponding to the chloride content in the original concrete, e.g. the concrete in between the surface parts shows no signs of chloride ingress.
- The results for 4 cores from the 400 mm thick segment concrete from the bored tunnel show a similar picture, with increased chloride contents to a depth of 20-22 mm from the outside exposed surface and 18-22 mm from the inside surface (air side). The concrete in between the surface parts has a very low chloride content corresponding to the chloride content in the original concrete, e.g. the concrete in between shows no signs of chloride ingress.
- In all cut and cover cores and in two cores from the bored tunnel (B1 and B2) the increased levels of chloride are of very low magnitude, and further of similar low magnitude on the outside as well as on the inside surface. The levels of chloride on the surface near regions are so low that long time chloride exposure seems questionable as even low w/c concretes normally in the outer few millimetres bind chlorides from e.g. seawater to much higher levels than found here.
- In two cores, B4 and B5 from the bored tunnel, the chloride levels are higher, both at the outside and inside surfaces. These results indicate that chloride exposure has taken place for these cores.
- The finding that the inside concrete surface (air side) for B4 and B5 shows a similar chloride profile as the outside surface is not easily explained. Evaporation and accumulation of chlorides from the background chloride content due to evaporation from the inside surface are not assumed to be the main causes - in this case, all cores should show an increased chloride content at a similar level at the inside surface. This is not the case. Leaking joints seem to be a more reasonable explanation, if the exposure time has been long.
- The in-situ diffusion coefficients (determined by profile grinding) for the cores are less than 1.0 and $1.5 \times 10^{-13} \text{ m}^2/\text{s}$. They are low and at a level corresponding to e.g. concrete edge beams exposed to salt spray from traffic (results from the Fiskebæk bridge, for a similar concrete type, exposed 13 years⁷).
- The results of the chloride migration coefficient tests confirm a concrete of high quality both for the bored tunnel and the cut and cover tunnel concrete. The measured chloride migration coefficient is 4-5 times higher than the in-situ diffusion coefficient.

5. CONCLUSIONS AND FINAL REMARK

From the in-situ investigations a number of conclusions may be drawn:

- Self-desiccation is a major factor for moisture transport in HPC.
- Only the outer exposed surface (to a depth of 25-30 mm) of submerged HPC are influenced by water-uptake (water side) or drying out (air side).
- The internal concrete is in a state of moisture equilibrium, with low to medium relative humidity values and degrees of vacuum saturation corresponding to a concrete undergoing self-desiccation.
- HPC will never be saturated because of the self-desiccation and the extremely slow moisture flow through the gel pores.
- 800 mm thick concrete tunnel sections (cut & cover tunnel) showed increased chloride contents near the outer as well as the inner wall surfaces. The concrete in-between showed a chloride content corresponding to the original content (background value). The increased values are of low magnitude. The inside values show no clear correlation with observations of possible leaking cracks.
- 400 mm thick concrete tunnel elements (bored tunnel) show a similar picture with increased chloride contents on the outside and inside exposed surfaces, whereas the concrete in-between shows a chloride level corresponding to background values. High chloride levels on the inside surface of the tunnel may be attributed to leaking joints, etc. as evaporation and accumulation of the background chlorides cannot implicate such high chloride contents alone.
- For both tunnel types there is no indication that a water or chloride transport takes place through the thickness of the walls after 12 years in service. The "swimming pool theory" does not seem applicable for the concrete types in question (HPC); the observations are more in line with percolation and diffusion theories⁵.

The results of the in-situ investigations are a first step to get a more clear picture about the moisture and chloride transport of submerged HPC. An up-dating of existing deterioration models will, however, require more background information knowledge (in particular on exposure conditions, concrete composition and microstructure of the exposed concrete) which combined with additional in-situ investigations will allow a more thorough evaluation of the findings. Adequate follow-up activities are envisaged.

6. REFERENCES

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