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Self-healing of cracks in concrete exposed to different types of water : effect on chloride penetration

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LUND INSTITUTE OF TECHNOLOGY
LUND UNIVERSITY

Division of Building Materials

**SELF-HEALING OF CRACKS IN CONCRETE
EXPOSED TO DIFFERENT TYPES OF WATER**

Effect on chloride penetration

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FOREWORD

This project was funded by the *Development Fund of the Swedish Construction Industry (SBUF)*, *Vattenfall Research and Development AB*, and *Skanska AB*. We are grateful for their support.

Planning of the practical of the exposure tests and execution of these tests in our laboratory were performed by our colleagues Bo Johansson and Bengt Nilsson. Their efforts are highly appreciated.

The analysis of mineral composition of precipitations in the cracks and analysis of chloride ingress in cracks were performed at the Swedish Cement and Concrete Institute in Stockholm. The following persons were involved, Mariusz Kalinowski, Leif Fjällberg, Jan Trägårdh, and Camilla Westerholm. Their work was central for the result of this investigation. We thank them for excellent work.

The project is divided in two parts. Results of the first part is presented in Fagerlund&Hassanzadeh (2010).

Lund, September 2011

Göran Fagerlund

Manouchehr Hassanzadeh

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1. SUMMARY

Step 1: 1 year exposure: 18 specimens were exposed for 1 year to two different moisture conditions; (i) exposure type 1 - completely immersed, (ii) exposure type 2 - cyclic immersion and drying.

Step 2: 28 month exposure: 16 specimens were exposed for 28 months to three different moisture conditions; (i) exposure type 1 - completely immersed, (ii) exposure type 2 - cyclic immersion and drying, (iii) exposure type 3 - transport from the interior towards the crack.

The three exposure types are illustrated by Figure 10.3.

In both steps only one type of concrete was used; w/c 0,40, alkali sulfate resistant Portland cement (this is the concrete type used in Swedish bridges and other heavily exposed structures).

The crack width at its tip was 0,2 mm and 0,4 mm. The crack was mechanically locked during the test (except for 2 specimens where relaxation of the crack could occur). The crack was unloaded, i.e. the crack was not exposed to compression. The cover thickness was 55 and 75 mm.

Both steps in the investigation are summarized below.

Visual observations using photographs of the crack along its length were made before and after exposure, Chapter 13.1-13.2. Observations of the crack on its first centimeter from the tip are:

- There are clear signs of self-healing of cracks immersed in sea water (exposure type 1). 0,2 mm cracks seem to obtain somewhat more self-healing than 0,4 mm cracks.
- There seems to be about the same amount of self-healing as at permanent immersion when 0,2 mm cracks are exposed to cyclic immersion in sea water and drying (exposure type 2), but less healing of 0,4 mm cracks.
- Cracks immersed in brackish water seem to obtain some healing as in sea-water, while there are no real signs of healing in tap water.
- There is no self-healing in any crack exposed to transport from the inner of the concrete towards the crack (exposure type 3).
- Visually there is not more healing after 28 months than after 1 year. Measurements of chloride penetration, however, contradict this statement.

Observations on bigger depth from the crack tip (>3 cm) also show signs of healing, especially for immersion in sea water.

The composition of precipitations in the crack were made by SEM combined with BSE and EDS, Chapter 15.3. The crack surface with its precipitations was photographed.

Results are:

- In cracks immersed in sea water, the most frequent precipitation is needle-shaped crystals of ettringite type.
- In cracks cyclically exposed to sea-water immersion and drying, the crack surface is covered by $Mg(OH)_2$ (brucite). Big amount of crystals of $Ca(OH)_2$ and ettringite are present.
- In cracks immersed in brackish water, ettringite occurs together with $CaCO_3$ crystals.

- In cracks exposed to transport from the inner of the concrete (exposure type 3), crystals of $\text{Ca}(\text{OH})_2$ and CaCO_3 are present. Besides there are signs of alkali-silica gel which is astonishing since low alkali cement and non-reactive aggregate were used.
- In cracks immersed in tap water $\text{Ca}(\text{OH})_2$ and CaCO_3 crystals and some ettringite is present.
- There are no big differences in the composition of precipitation between 1 year exposure and 28 month exposure.
- The amount of precipitation could not be quantified by the technique used.

The chloride concentration in the crack wall on different depths from the crack tip was determined by ion selective electrode on samples taken from the wall. The cement content was determined by EDTA. From the measurements chloride profiles could be drawn, and the chloride transport coefficient (chloride diffusivity) be evaluated, Chapter 15. 5-15.6. After 28 months exposure a comparison is made with the chloride profile in un-cracked concrete.

Results are:

- For all exposure types, the chloride concentration decreases with increasing distance from the crack tip which indicates that healing has substantially reduced the inflow of chloride.
- For cracks immersed 28 months in sea-water, the chloride in cracks is somewhat higher than in the un-cracked concrete. The calculated chloride diffusivity for 55 mm cover is $4,3 \cdot 10^{-12} \text{ m}^2/\text{s}$ compared with $3,2 \cdot 10^{-12} \text{ m}^2/\text{s}$. There is no difference between 0,2 and 0,4 mm wide cracks.
- For concrete cover 75 mm, the diffusivity is a bit higher than for 55 mm cover. However, the difference is not big.
- For cracks immersed in brackish water the chloride diffusivity is of the same order as for cracks in sea-water.
- The calculated diffusivity in cracks is lower after 28 months exposure indicating that self-healing has progressed with time. For immersion of 0,4 mm cracks the diffusivity is $4,3 \cdot 10^{-12} \text{ m}^2/$ after 28 months compared with $9,4 \cdot 10^{-12} \text{ m}^2/$ after 1 year.

2. INTRODUCTION

It is well-known from many investigations that damaged concrete can restore some of its strength, or the whole strength, under moist conditions. This healing, often called *self-healing*, is supposed to depend on two main mechanisms:

- Continued hydration of cement. The hydration products fill the crack more or less completely. The mechanism ought to most active when cracks appear early when there is still a substantial amount of un-reacted cement.
- Precipitation of $\text{Ca}(\text{OH})_2$ and CaCO_3 within the crack. The latter component is formed by reaction between calcium ions in pore water and CO_3 -ions dissolved in this.

There are almost no investigations of the effect of self-healing on chloride penetration in the crack.

In order to avoid early start of reinforcement corrosion it is normally prescribed in concrete norms and standards that the crack width (at the concrete surface) in concrete exposed to chloride-containing water (sea or de-icing salt) shall not exceed a certain value. This is sometimes fixed at 0,1 mm and sometimes at 0,2 mm, but seldom more than these values. In order to limit the crack width to these low values a substantial amount of reinforcement is often required. This cause extra cost and will often cause problems during production of the structure. If effective self-healing would occur, so that chloride ingress was not much higher than in the un-cracked concrete, it ought to be possible to increase the maximum allowed crack width.

In this report the results of an investigation of self-healing of cracks during three different moisture conditions, and in three different water types, are presented. The focus is on chloride penetration.

The ultimate aim of the project is to find out if cracks open to the surface in concrete exposed to sea water can heal so that chloride ingress in concrete through the crack is effectively obstructed. If this is the case it might be possible to accept wider cracks in concrete than is allowed in present rules.

In order to be able to cope with this aim the following observations were made:

- Observations, visually and experimentally, of the *amount and type of precipitations in cracks* of two different widths (0,2 and 0,4 mm) in concrete after exposure for more than 2 years (28 months) to different types of water (sea water, brackish water or tap water) and during different exposure types (immersed, cyclic immersion/drying, and transport from inside towards the drying surface).
- Observations of the effect of self-healing on the chloride ingress in the crack walls for the three types of exposure.

The investigation is divided in two steps:

- *Step 1:* Observations after 1 year exposure. Detailed results presented in Fagerlund&Hassanzadeh (2010).
- *Step 2:* Observations after 28 month exposure. Results presented in the present report.

3. CONCRETE

One type of concrete was used in the investigation. It has the following characteristics:

- *Cement type*: Swedish portland cement with low alkali, high sulphate resistance, moderate heat of hydration. The cement is marketed under the name *Anläggningcement* and is the main cement used in Swedish bridge building since about 25 years. The cement was also used for the Öresund bridge. The cement characteristics are shown in Table 3.1.
- *water/cement ratio*: 0,40. This value is prescribed in Sweden for concrete under severe exposure to sea water or de-icing salt.
- *Concrete composition*: The mix proportions are shown in Table 3.2.

Table 3.1: Cement characteristics

Property	Value
Type according to EU and Swedish Standard	CEM I 42,5N BV/SR/LA
C ₃ S	53%
C ₂ S	25%
C ₃ A	2%
C ₄ AF	13%
(Na ₂ O) _{equiv} (soluble)	0,4%
Filler content	0%
Specific surface	320 m ² /kg
Strenth	
1 day	10 MPa
28days	54 MPa

Table 3.2: Mix characteristics

Ingredient	Value
w/c-ratio	0.40
cement	440 kg/m ³
water	176 kg/m ³
gravel 0-8 mm	1120 kg/m ³
stone 8-12 mm	630 kg/m ³
superplastiziser (melamine)	~0,9 kg/m ³
cube strength at 28 days	84 MPa

The curing procedure was as follows:

- 1:st day: Specimens stored in mould, top surface covered by plastic foil
- 2-14 days: Stored in lime-saturated water
- Day 14: Crack öfabricatedö; see chapter 5.
- Day 14: Placed in different baths; see chapter 8.
- Exposure in the bath for 12 months or 28 months.

4. SPECIMENS

Specimens 150 mm wide, 200 mm high and 300mm long were cast in a mould with plywood sides and bottom. Each end of the mould was made of two stainless steel tubes with rectangular cross-section welded together to form a beam with width 150 mm and height 320 mm. At the lower part of each steel beam holes were made for two threaded stainless steel rods which were cast into the concrete. These rods were used for transferring to concrete the tensile force occurring in the beam during bending used for pre-cracking.

At the top of each steel beam two holes were made for fastening two threaded stainless steel rods which were used for maintaining the initial crack width during immersion.

Two ribbed reinforcement bars with diameter 12 mm were fixed in the mould so that a certain cover (55 or 75 mm) counted from the bottom side was obtained.

A steel strip 3 mm wide and 3 mm thick was fixed on the bottom of the mould at its mid-section. Its function was to create a notch in the specimen which was used for localizing the crack during bending.

A drawing of the specimen is shown in figure 4.1. Figure 4.2 and 4.3 show photos of the specimen directly after casting and after de-moulding.

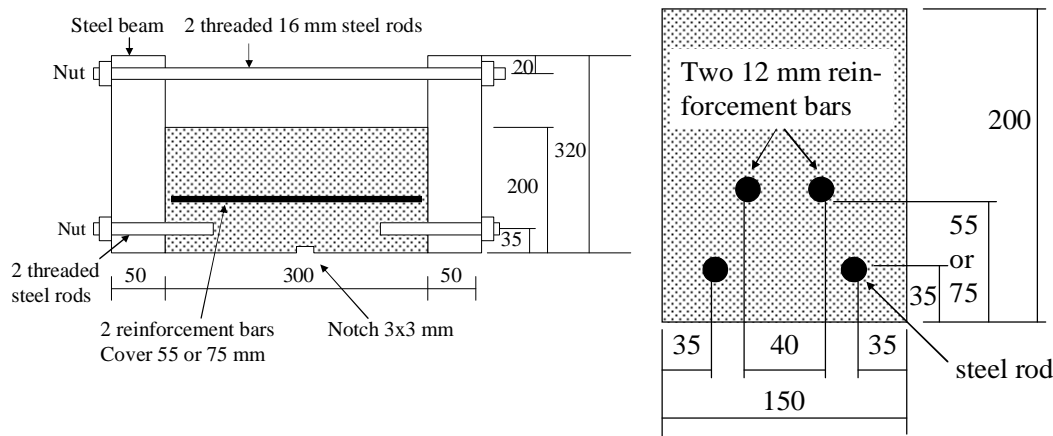


Figure 4.1: Specimen seen from the side and cross-section.

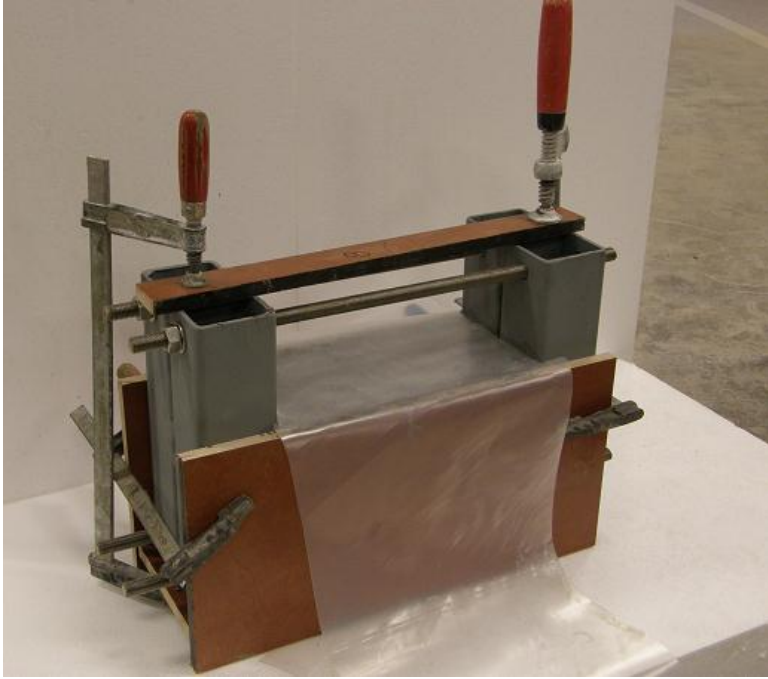


Figure 4.2: Specimen directly after casting.

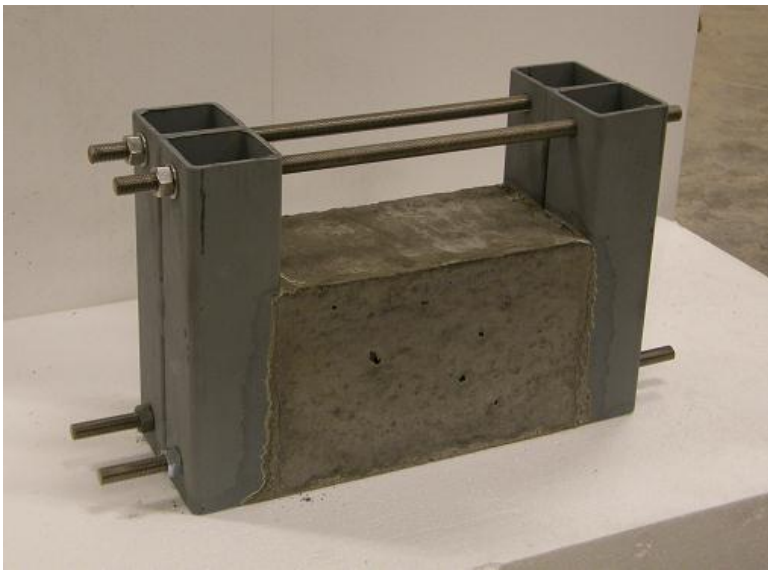


Figure 4.3: Specimen after de-moulding.

- In total 34 specimens were cast. 18 of these were tested after 1 year exposure. Results are presented in Fagerlund&Hassanzadeh (2010). The other 16 specimens were tested after about 28 month exposure. Results of these specimens are presented in the present report.

5. PRE-CRACKING

A crack initiating at the bottom of the specimen was produced in the specimen when this was 2 weeks old. The specimen was placed in a test machine on two supports designed in such a way that no twisting of the specimen could occur. Thereby, the crack width would be the same on both sides of the specimen. Two extensometers were mounted on the bottom surface. They were supported by screws mounted on cast-in nuts on both sides of the notch. Figure 5.1 shows the bottom surface with cast-in nuts.



Figure 5.1: Cast-in nuts for mounting two extensometers across the notch.

Pressure was applied on the upper surface of the specimen at its mid-section. A crack was induced at the notch. Pressure was increased until the extensometers indicated that the crack mouth opening aimed at was reached (0,2 or 0,4 mm). Then, the nuts on the upper threaded bars was tightened and locked by another nut so that the crack was locked. When the pressure was released it was controlled that the crack maintained its initial width and that no relaxation of the crack occurred.

The test arrangement is shown in figure 5.2.

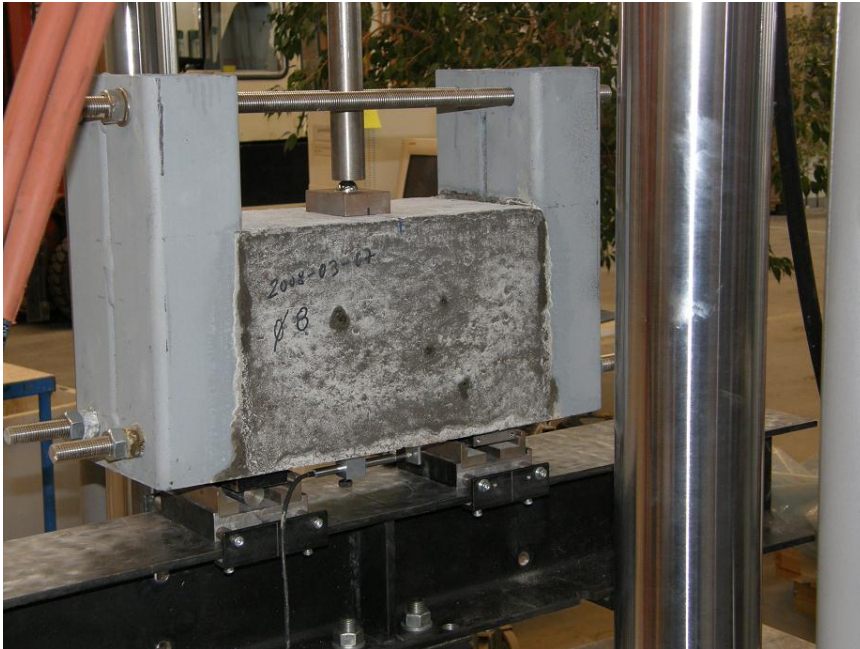


Figure 5.2: Test assembly for creating a crack in the specimen.

6. CRACK WIDTH

Two widths of the crack opening were used:

- 0.2 mm
- 0.4 mm

0.2 mm is the biggest crack accepted in the Swedish concrete standard for concrete exposed to sea water or de-icing salt. The crack width 0.4 mm was used for most of the specimens.

7. PHOTOGRAPHY OF CRACKS BEFORE EXPOSURE

Photos were taken of the crack before it was sealed, i.e. before the concrete placed in the bath. 5 to 8 photos were taken along the crack on each side of this. Each photo covered about 12 mm of the crack length. Examples of photos of two cracks are shown in figure 7.1.



Figure 7.1: Photography of cracks before exposure. 75 mm cover. cm-scale indicated.

Left: Crack width 0.4 mm (specimen H75-4-1-2 left side).

Right: Crack width 0.2 mm (specimen H75-2-1-2 left side).

8. SEALING OF CRACKS

After taking photos of the crack and before placing the specimens in the bath, the sides of the specimens were sealed by moisture impermeable aluminium tape which extended 75 mm on each side of the crack. The seal was made in two steps, see figure 8.1:

- Step 1: an inner 5 cm wide aluminium tape which was used to avoid soiling the concrete surface by the outer bituminous tape so that undisturbed photos of the surface could be taken after exposure.
- Step 2: an outer 15 cm wide aluminium tape coated on the inside by a thick bituminous sticky layer.

Sealing was made in order to avoid ingress of water or salt water from the crack sides. All ingress had to be one-directional along the crack.

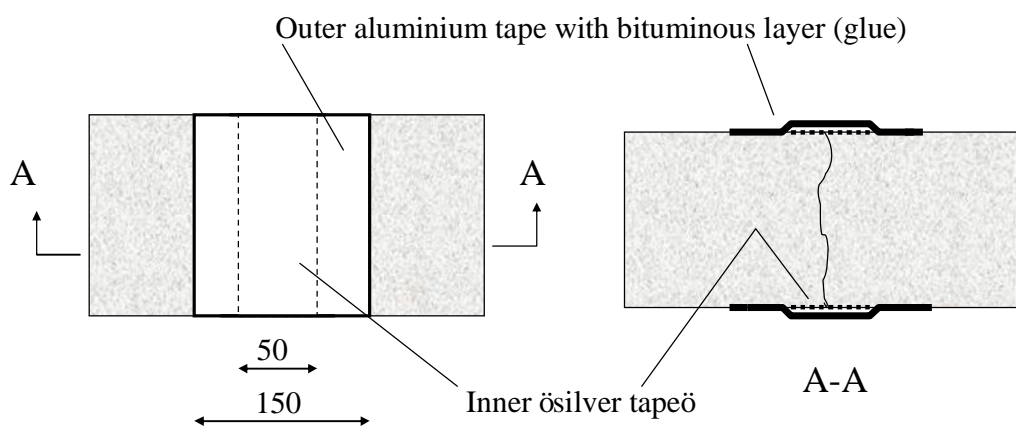


Figure 8.2: Sealing of the sides of the crack.

9. WATER USED FOR EXPOSURE OF SPECIMENS

3 types of water were used for exposure of the specimens:

- Sea water collected from the west-coast of Sweden. The salt content is 24 gram per litre and the chloride ion content 13 gram per litre.
12 specimens were exposed.
- Brackish water collected from south Baltic Sea. The salt concentration is 8 gram per litre. The chloride ion concentration is 4.4 gram per litre.
2 specimens were exposed.
- Ordinary tap water.
2 specimens were exposed.

The basins used for storage of the specimens were covered by plastic lids (except exposure type 3). The water level was measured regularly and evaporated water was replaced by additional water so that the salt concentration remained constant.

10. WATER EXPOSURE

Three types of water exposure were used:

- Type 1: Permanently stored under water. The specimens were completely covered by water during 28 months. A basin with specimens is shown in figure 10.1.
- Type 2: Cyclic. 1 week immersed in water followed by 1 week in lab air. In total 55 cycles.
- Type 3: Water suction from the un-cracked side. The specimens were turned upside down and the un-cracked upper surface was immersed some millimetres in water. Drying in lab-air occurred from the cracked side. The specimens were stored in this way during 28 months. A basin with specimens is shown in figure 10.2.



Figure 10.1: Water exposure type 1; permanently under water.



Figure 10.2: Water exposure type 3: Capillary suction from the un-cracked top side.

The significance of the different exposure types used in this investigation are illustrated by Figure 10.3.

- Exposure type 1 represents parts of a structure permanently under water, like a concrete pier in salt water or a hydraulic structure in pure water.
- Exposure type 2 represents parts of a structure in the splash zone in salt water.
- Exposure type 3 represents parts of a structure a bit above the highest sea-water level.

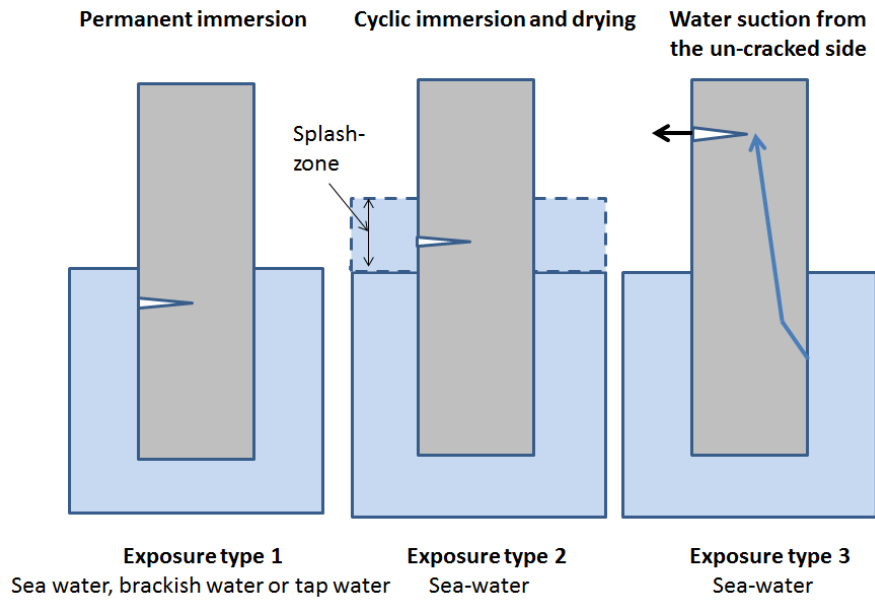


Figure 10.3: Exposure types considered in the investigation.

11. TEST SERIES - VARIABLES

Test series 1: Sea water from the Swedish west-coast

Variables:

- Crack width; 0.2 and 0.4 mm
- Concrete cover: 55 and 75 mm
- Exposure type: 1, 2, 3.
- Non-relaxed crack
- Open crack mouth

Crack width (mm)	Concrete cover (mm)	Exposure		
		Type 1; immersed	Type 2; cyclic	Type 3; water suction
0.2	55	H55-2-1-2 ¹⁾	H55-2-2-2	H55-2-3-2
	75	H75-2-1-2	H75-2-2-2	H75-2-3-2
0.4	55	H55-4-1-2	H55-4-2-2	H55-4-3-2
	75	H75-4-1-2	H75-4-2-2	H75-4-3-2

12 specimens

¹⁾ Specimen label

Test series 2: Brackish water from the Baltic Sea

Variables:

- Crack width: 0.4 mm
- Concrete cover: 55 and 75 mm
- Exposure type: 1

Crack width (mm)	Concrete cover (mm)	Exposure
		Type 1; immersed
0.4	55	S155-4-1-2-Ö
	75	S175-4-1-2-Ö

2 specimens

Test series 3: Tap water

Variables:

- Crack width: 0.4 mm
- Concrete cover: 55 and 75 mm
- Exposure type: 1

Crack width (mm)	Concrete cover (mm)	Exposure
		Type 1; immersed
0.4	55	S155-4-1-2-R
	75	S175-4-1-2-R

2 specimens

12. PHOTOGRAPHS OF CRACKS AFTER 28 MONTH EXPOSURE

After about one year exposure the crack seal was removed. Thereafter photos of the cracks were taken in the same manner as before exposure. Examples of photos are given in figure 12.1 which shows the same cracks as are shown in figure 7.1 before exposure. There is a clear indication of healing, particularly for the thinner crack, which seems to be almost completely healed on 2 cm from the crack tip.

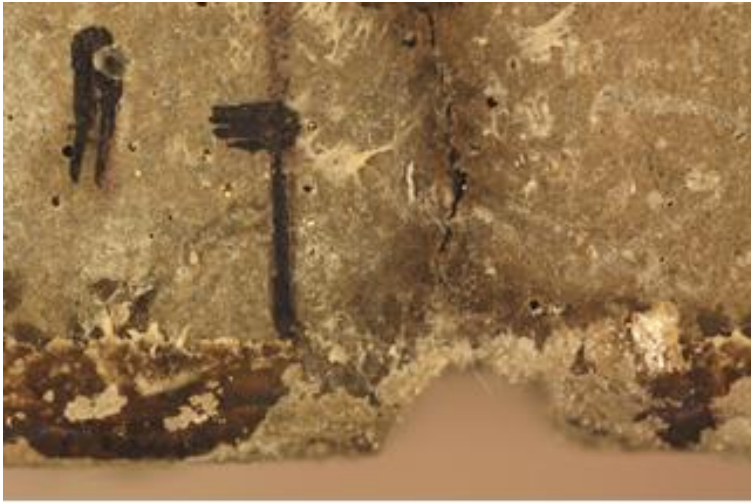


Figure 12.1: Photographs of cracks after exposure. The same specimens as in figure 7.1.

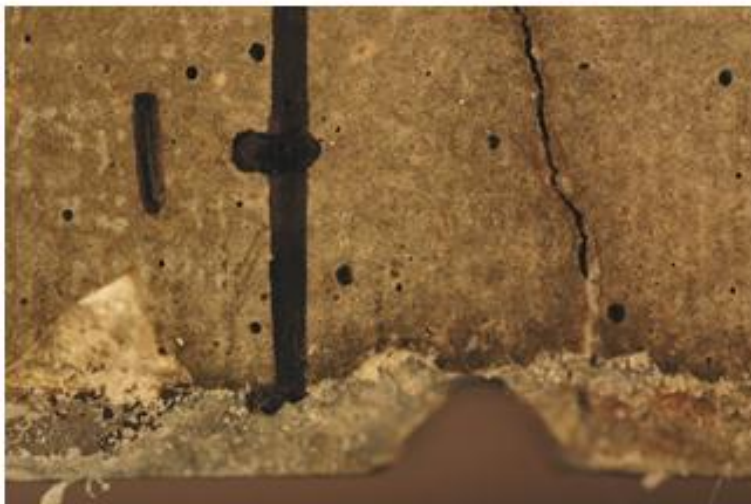
Left: Crack width 0.4 mm (specimen H75-4-1-2 left side).

Right: Crack width 0.2 mm (specimen H75-2-1-2 left side).

Magnifications of photos of the lowest part of the crack after 28 month exposure for all 16 specimens are shown in figure 12.2-12.7. Only one side of the specimens is shown. The other side is similar to the side shown.



Permanent immersion
H75-2-1-2



Cyclic immersion
H75-2-2-2



Water suction from the
un-cracked side
H75-2-3-2

Figure 12.2: 0.2 mm crack after 28 month exposure to sea water. Concrete cover 75 mm.



Permanent immersion
H75-4-1-2

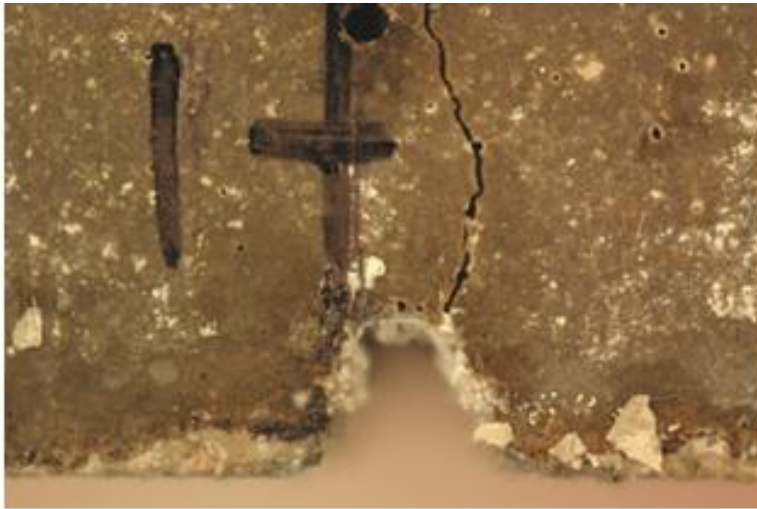


Cyclic immersion
H75-4-2-2

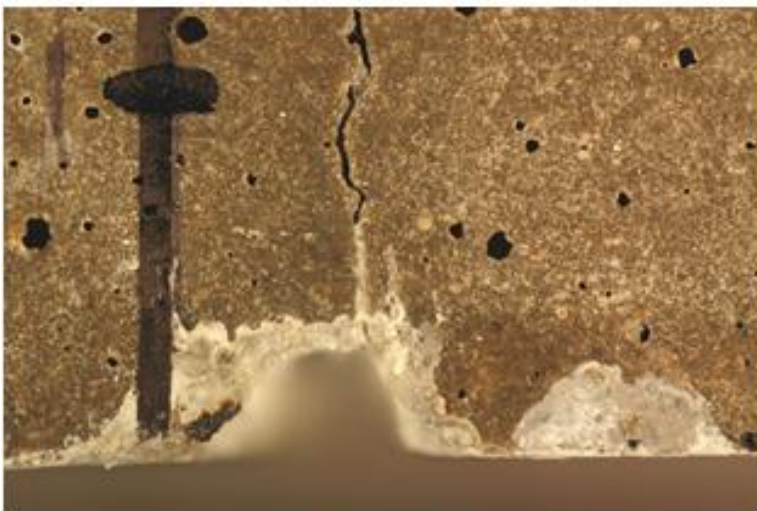


Water suction from the
Un-cracked side
H75-4-3-2

Figure 12.3: 0.4 mm crack after 28 month exposure to sea water. Concrete cover 75 mm.



Permanent immersion
H55-2-1-2



Cyclic immersion
H55-2-2-2

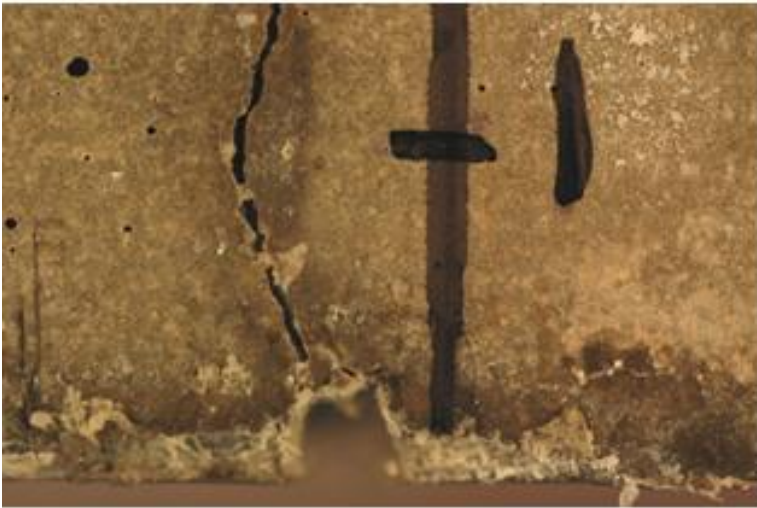


Water suction from
the un-cracked side
H55-2-3-2

Figure 12.4: 0.2 mm crack after 28 month exposure to sea water. Concrete cover 55 mm.



Permanent immersion
H55-4-1-2



Cyclic immersion
H55-4-2-2



Water suction from the
un-cracked side
H55-4-3-2

Figure 12.5: 0.4 mm crack after 28 month exposure to sea water. Concrete cover 55 mm.

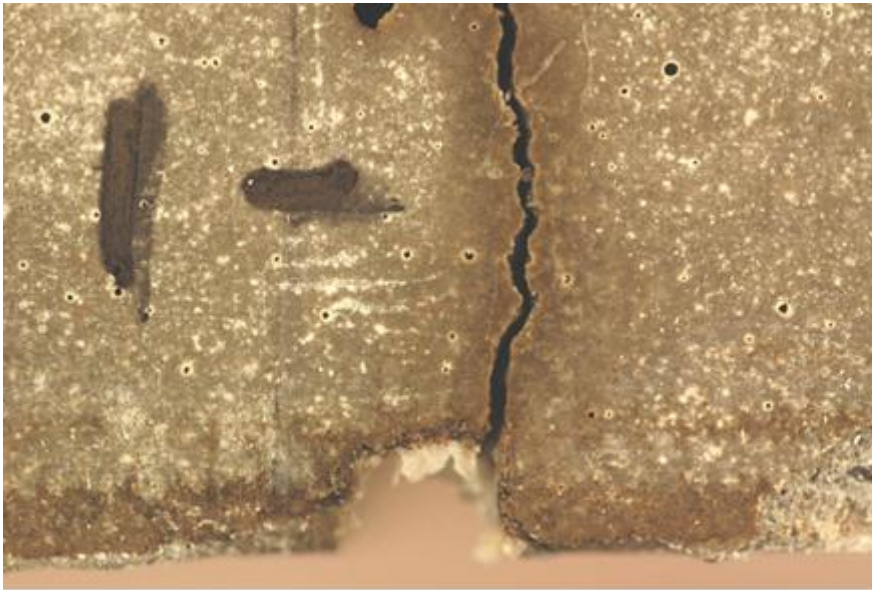


Permanent immersion
S175-4-1-2-Ö

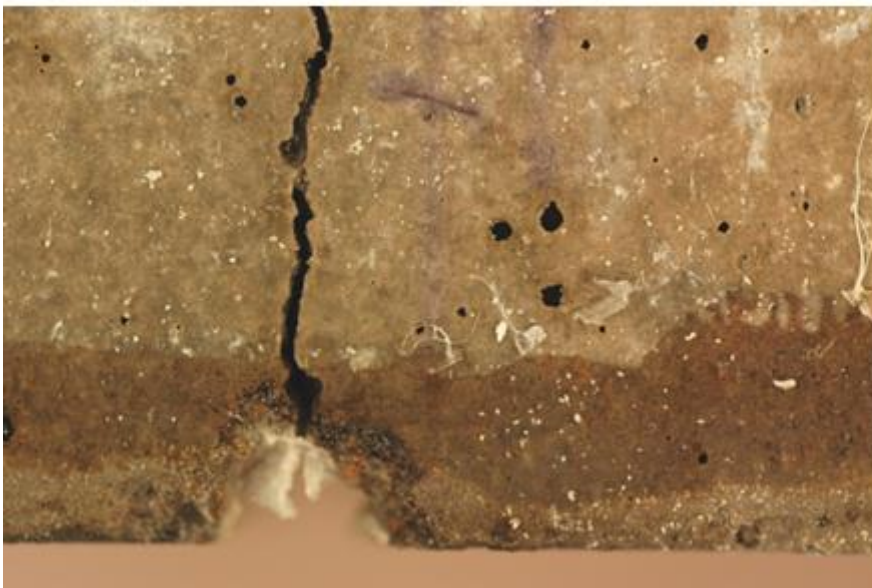


Permanent immersion
S155-4-1-2-Ö

*Figure 12.6: 0.4 mm crack after 28 month permanent exposure to brackish water.
Upper: 75 mm cover. Lower: 55 mm cover*



Permanent immersion
S175-4-1-2-R



Permanent immersion
S155-4-1-2-R

*Figure 12.7: 0.4 mm crack after 28 month permanent exposure to pure water.
Upper: 75 mm cover. Lower 55 mm cover.*

Photos of the entire crack from its tip to about 3 to 4 cm depth are shown in APPENDIX 1. In each picture, comparison is made of the crack before exposure and after 28 month exposure. Only one side of the crack is shown.

The following visual observations are made for the lowest part of the crack:

- There are clear signs of self-healing of cracks when concrete is permanently immersed in sea water, especially for the crack width 0,2 mm; Figure 12.2, and A1.1.
- Self-healing is less clear for crack width 0,4 mm when immersed in sea water; Fig 12.5 and A14.
- Cyclic immersion and drying in sea water seems to give the same amount of self-healing as permanent immersion for crack width 0,2 mm (Fig 12.2 and A1.7), but almost no healing for crack width 0,4 mm; Fig 12.2 and A1.11.
- Water suction from the un-cracked side gives no visual healing for any crack width.
- There is a certain self-healing close to the crack tip at immersion in brackish water (Fig 12.6 and Fig A1.15) but no healing at immersion in pure water (Fig 12.7 and Fig A1.16).

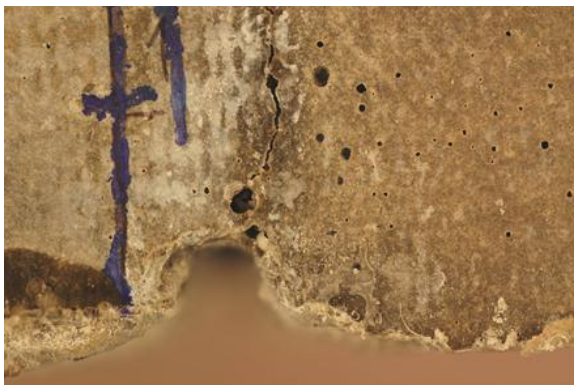
Magnified photos of cracks on about 3 cm distance from the crack opening for the same specimens as shown in the figures above are shown in APPENDIX 2. The following visual observations are made for the crack on 3 cm depth:

- Permanent immersion in sea water seems to give some self-healing of 0,2 mm cracks (Fig A2.1), but no healing of 0,4 mm cracks (Fig A2.2, A2.4).
- Cyclic immersion in sea water and drying seems to give no healing.
- At immersion in brackish water or pure water there are no clear signs of self-healing.

13. PHOTOGRAPHS OF CRACKS AFTER 12 AND 28 MONTH EXPOSURE A COMPARISON

Photos of cracks after 12 month exposure are presented in Report (1). They can be compared with photos in the present report. Some examples of such comparisons are given in Figure 13.1-13.12. Note: The exposure type water suction from the un-cracked side was not included in the 12 month tests.

A: Specimens permanently immersed in sea water

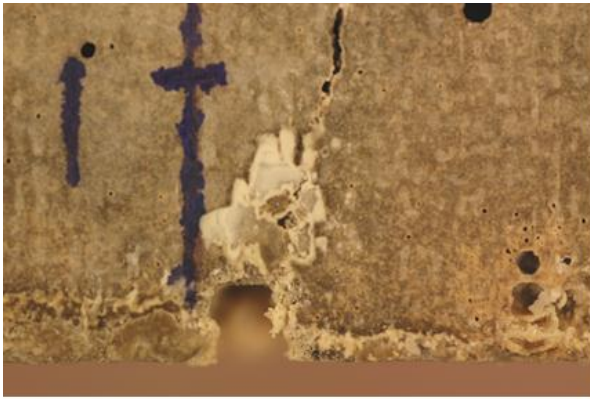


12 month exposure
Specimen H75-2-1-1



28 month exposure
Specimen H75-2-1-2

Figure 13.1: Crack width 0.2 mm. Cover 75 mm. Permanent immersion in sea water for 12 and 28 months.



12 month exposure
Specimen H75-4-1-1



28 month exposure
Specimen H75-4-1-2

Figure 13.2: Crack width 0.4 mm. Cover 75 mm. Permanent immersion in sea water for 12 and 28 months.



12 month exposure
Specimen H55-2-1-1



28 month exposure
Specimen H55-2-1-2

Figure 13.3: Crack width 0.2 mm. Cover 55 mm. Permanent immersion in sea water for 12 and 28 months.



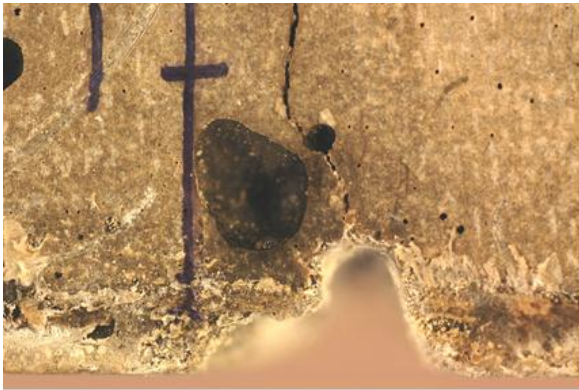
12 month exposure
Specimen H55-4-1-1



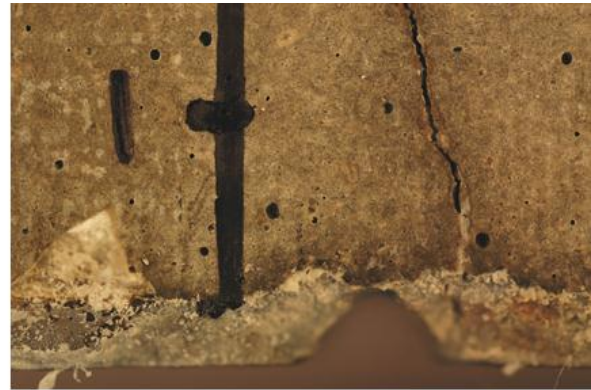
28 month exposure
Specimen H55-4-1-2

Figure 13.4: Crack width 0.4 mm. Cover 55 mm. Permanent immersion in sea water for 12 and 28 months.

B: Specimens cyclically immersed in sea water

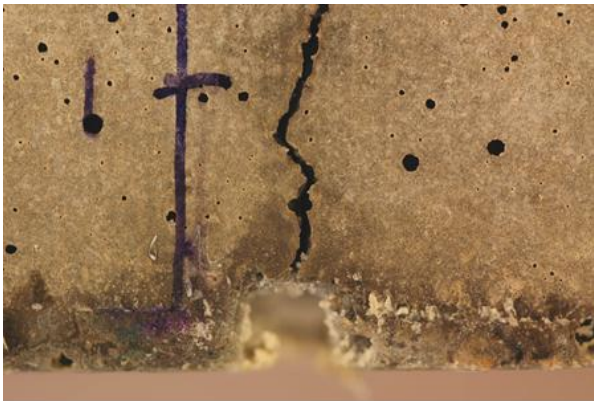


12 month exposure
Specimen H75-2-2-1



28 month exposure
Specimen H75-2-2-2

Figure 13.5: Crack width 0.2 mm. Cover 75 mm. Cyclic immersion in sea water for 12 and 28 months.



12 month exposure
Specimen H75-4-2-1



28 month exposure
Specimen H75-4-2-2

Figure 13.6: Crack width 0.4 mm. Cover 75 mm. Cyclic immersion in sea water for 12 and 28 months.



12 month exposure
Specimen H55-2-2-1



28 month exposure
Specimen H55-2-2-2

Figure 13.7: Crack width 0.2 mm. Cover 55 mm. Cyclic immersion in sea water for 12 and 28 months.



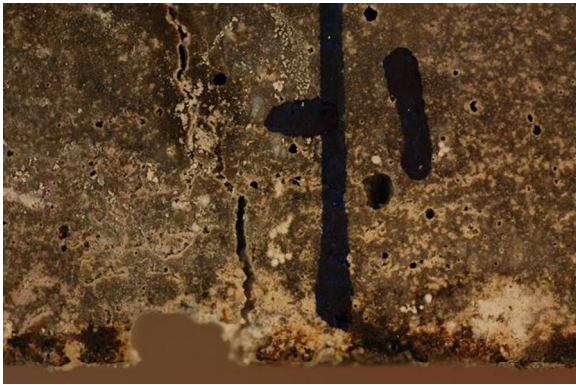
12 month exposure
Specimen H55-4-2-1



28 month exposure
Specimen H55-4-2-2

Figure 13.8: Crack width 0.4 mm. Cover 55 mm. Cyclic immersion in sea water for 12 and 28 months.

C: Specimens permanently immersed in brackish water



12 month exposure
Specimen S175-4-1-1Ö



28 month exposure
Specimen S175-4-1-2Ö

Figure 13.9: Crack width 0.4 mm. Cover 75 mm. Permanent immersion in brackish water for 12 and 28 months.



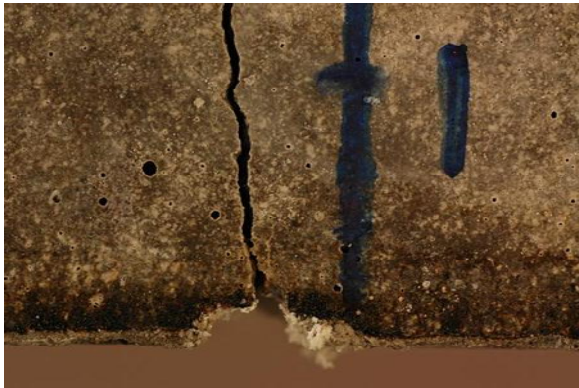
12 month exposure
Specimen S155-4-1-1Ö



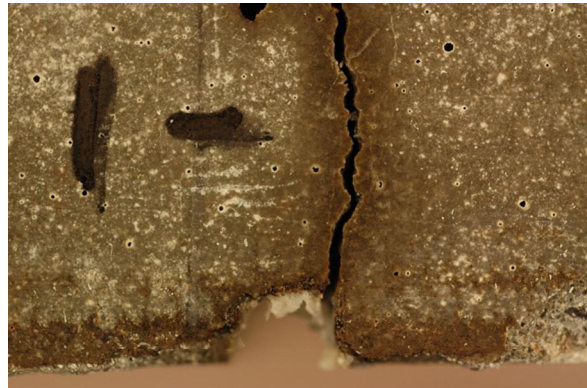
28 month exposure
Specimen S155-4-1-2Ö

Figure 13.10: Crack width 0.4 mm. Cover 55 mm. Permanent immersion in brackish water for 12 and 28 months.

D: Specimens permanently immersed in pure water

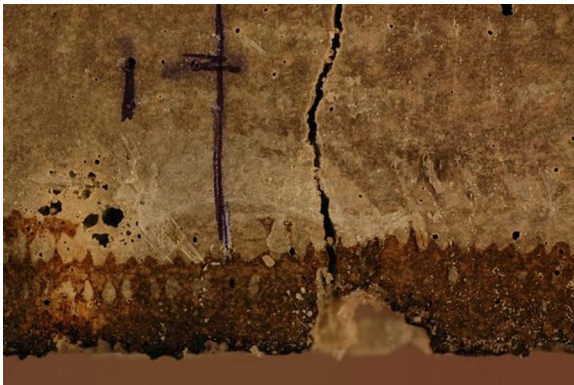


12 month exposure
Specimen S175-4-1-1R

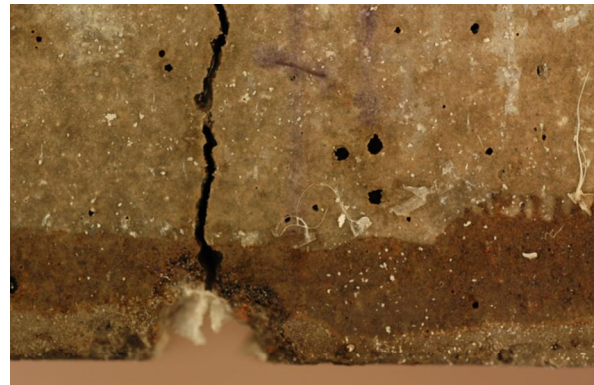


28 month exposure
Specimen S175-4-1-2R

Figure 13.11: Crack width 0.4 mm. Cover 75 mm. Permanent immersion in pure water for 12 and 28 months.



12 month exposure
Specimen S155-4-1-1R



28 month exposure
Specimen S155-4-1-2R

Figure 13.12: Crack width 0.4 mm. Cover 55 mm. Permanent immersion in pure water for 12 and 28 months.

According to the figures above there are no clear indications of a more extended self-healing in specimens that have been exposed for 28 months compared with specimens that were exposed for 12 months.

14. DRILLING OF CORES AFTER EXPOSURE

After terminated exposure a 10 cm core was drilled centrally in the specimen from its bottom side along the crack. Drilling was made with water-cooled drill. An example of the specimen after drilling is shown in figure 14.1. An example of a drilled-out core is shown in figure 14.2.



Figure 14.1: Example of a specimen after the core has been drilled out.

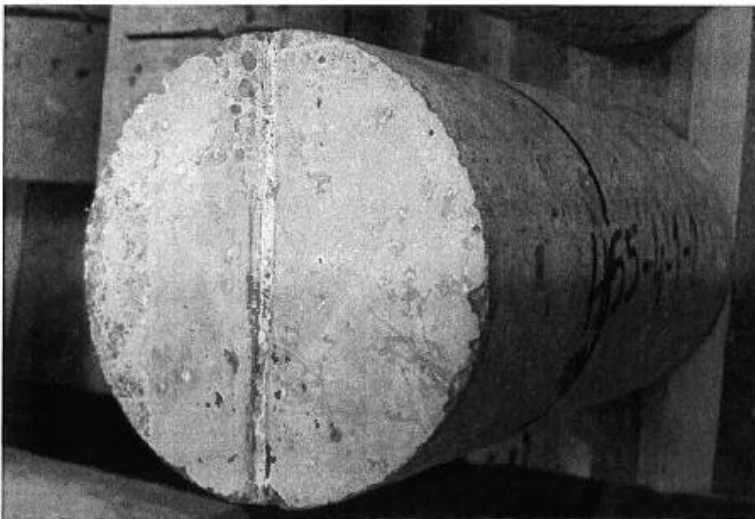


Figure 14.2: Example: core drilled out from specimen H55-4-1-2 (55 mm cover, crack width 0.4 mm, permanently exposed to pure water).

Photo: Report (Kalinowski&Trägårdh) (2011).

After drilling, the cores were immediately wrapped in plastic foil and sent to the Swedish Cement and Concrete Research Institute (CBI) for testing.

15. ANALYSIS OF MINERALS AND CHLORIDE CONCENTRATION IN CRACK WALLS

15.1 Location of tests

The cores were investigated at the Swedish Cement and Concrete Research Institute (CBI) in Stockholm. The following investigations were made:

1. Visual inspection of crack walls.
2. Composition and morphology of minerals precipitated in the crack on three different depths from the crack mouth (5, 25 and 50 mm).
3. Concentration of chloride ions in the outermost few millimetres (<5 mm) of the crack wall on three different depths from the crack opening (5-10, 15-20, 25-30 and 35-40 mm).

Location of the test areas are shown in figure 15.1.

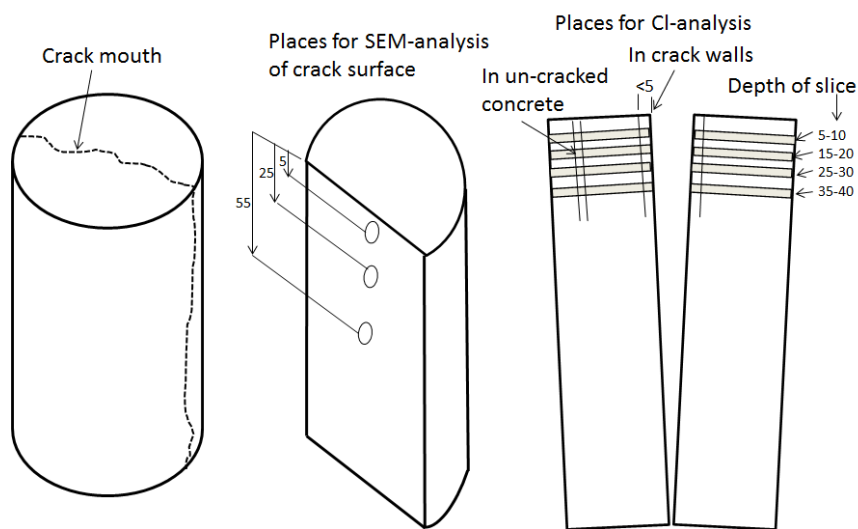


Figure 15.1: Core and places where samples were taken from the crack walls.

All test results have been published in a report by Kalinowski&Trägårdh (2011). Results from this report are presented below.

15.2 Visual inspection of crack walls

The outer 55-60 mm of the core was removed from the rest by saw. The two crack walls were investigated visually by means of a stereo magnifying glass with 40 times magnification.

The presence of precipitations on the crack wall were observed for all specimens, except for two specimens with 55 mm cover that had been exposed to water uptake from behind the crack (exposure type 3, specimens H55-4-3-2 and H55-2-3-2). The precipitations consist of very fine-porous and thin coatings on the crack wall. Normally the crack wall is covered to a depth of 50 mm or more.

Bigger crystals (mm-size), seemingly bridging the crack walls, appear in some specimens.

The biggest amount of precipitation was found for two specimens exposed to cyclic immersion in sea water and drying (specimens H55-2-2-2 and H55-4-2-2). Specimens permanently exposed to sea water, brackish water or pure water contained somewhat smaller amount of precipitation.

15.3 Mineral composition of precipitations in cracks

Fragments from the crack surface for which mineral analysis was made were taken from a width of at least 25 mm on each distance from the crack mouth (5, 25 50 mm).

Minerals (individual crystals) precipitated in the crack surface was investigated by SEM equipped with back scattered electron detector (BSE) and energy dispersive X-ray spectroscope (EDS). Results from the EDS analyses were recalculated to oxides and the sum of oxides normalized to 100%. The analysis covers elements with atomic number 11 (Na) or higher. Furthermore a qualitative detection of carbon and oxygen was performed.

Types and composition of different precipitated compounds in the cracks of 9 specimens are described in Tables 15.1-15.5. Examples of photos of the crack walls are shown in APPENDIX 3. Many more photos are shown in the report by Kalinowski&Trägårdh (2011).

The following compounds were frequently observed on all depths from 5 to 50 mm:

1. *Specimens permanently immersed in sea water:*
Ca-Al-sulfate crystals with ettringite composition. $\text{Ca}(\text{OH})_2$ -crystals. Some Ba-sulfate crystals close to the crack tip.
2. *Specimens cyclically exposed to sea-water and drying:*
Surface covered by a mat of $\text{Mg}(\text{OH})_2$ (brucite). Big amount of big $\text{Ca}(\text{OH})_2$ crystals. Big amount of Ca-Al-sulfate crystals with ettringite composition.
3. *Specimens exposed to water suction from the un-cracked side:*
Crystals of $\text{Ca}(\text{OH})_2/\text{CaCO}_3$. Alkali-silica gel.
4. *Specimens permanently stored in brackish water:*
 CaCO_3 -crystals. Ca-Al-sulfate crystals with ettringite composition.
5. *Specimens permanently stored in tap water:*
Big amount of crystals of CaCO_3 and $\text{Ca}(\text{OH})_2/\text{CaCO}_3$. Some ettringite.

The following statements are made in the report by Kalinowski&Trägårdh (2011):

øPrecipitations on crack surfaces were observed in all specimens investigated by SEM. The precipitations consist of very fine-graded and thin coatings on the crack surfaces and bigger crystals and crystal aggregates. Chemical compounds precipitated are mainly calcium hydroxide, calcium carbonate and Ca-Al-sulfate with a composition which often corresponds to ettringite. í ..Precipitated crystals of calcium hydroxide, calcium carbonate and barium sulfate reach sizes that join the two crack surfaces. í The degree of precipitation in cracks can be described as low in all specimens. We have not observed any location on the investigated depths within the specimens where one can describe the crack as completely healed. Our judgement is that the precipitations within the depth 0-51 mm has not involved a healing to such an extent that it can obstruct penetration of moisture and chlorideö.

The last statement is partly contradicted by the observations of chloride penetration shown in paragraph 15.5.

Table 15.1: Element composition of precipitations in cracks.
Specimens permanently stored in sea water.

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
55 mm	0.2 mm	5 mm ¹⁾	Cubes	39-85 % CaO 5-30 % MgO 5-17 % SiO ₂ 3-5% SO ₃	H55-2-1-2 Fig A3.1
			Needles	65 % CaO 19 % SO ₃ 9 % Al ₂ O ₃ 6 % SiO ₂	
			Crystal aggregate irregular shape	88 % CaO 3-4 % SiO ₂ 3% SO ₃ 2-3% Al ₂ O ₃	
		50 mm ²⁾	Microcrystalline aggregate	53% CaO 19% SiO ₂ 10% Al ₂ O ₃ 10% SO ₃	
			Needles	49 % CaO 26% SO ₃ 19% Al ₂ O ₃ 5% SiO ₂	
			Hexagonal plates	55% CaO 25% Al ₂ O ₃ 6% SiO ₂ 2-3% SO ₃ 4-5% Fe ₂ O ₃	
			Small plates	96% CaO 3% SiO ₂	
		0.4 mm	5 mm ³⁾	Needles	
	Plates			98% CaO	
	Prismatic crystals			84-96% CaO	
	50 mm ⁴⁾		Short prisms	95% CaO 4% SiO ₂	
			Needles	55-% CaO 23 % SO ₃ 17% Al ₂ O ₃	
			Plates type 1	52% CaO 31-35% Al ₂ O ₃ 10-13% Cl ₂ O	
		Plates type 2	91-96% CaO 3-6% SiO ₂		

Comments from Kalinowski&Trägårdh (2011) are cited below.

1) The crack surface is covered by needle-shaped crystals of Ca-Al sulphate. In some area there are small cube-shaped crystals of CaCO₃.

2) The surface is covered by big and small plate-shaped crystals of Ca(OH)₂. Some are of the size 1 mm. There are a few small (<10µm) flat crystals of a Ca-Al-Cl compound with high content of Si and Fe. Aggregate of needle-shaped crystals of Ca-Al-sulfate with ettringite composition.

3) Needle-shaped crystals of Ca-Al-sulfate with ettringite composition. Single prismatic crystals of CaCO₃, <10µm.

4) Big plates of Ca(OH)₂. Size < 2mm. Flat crystals (<50µm) of Ca(OH)₂. Flat hexagonal crystals (<50µm) of a Ca-Al-Cl compound. Needle-shaped crystals of Ca-Al-sulfate with ettringite composition.

Table 15.1 Continued: Element composition of precipitations in cracks.
Specimens permanently stored in sea water.

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
75 mm	0.2 mm	5 mm ¹⁾	Crystal aggregates	85-93 % CaO 2-5 % SiO ₂	H75-2-1-2
			Flat crystals	65 % BaO 28 % SO ₃ 4 % CaO	
			Needles	53-57 % CaO 21% SO ₃ 15% Al ₂ O ₃ 4-6 % SiO ₂	
			Cubic crystals	89% CaO 3% SiO ₂	
			Small flat Crystals	86% CaO 8% SiO ₂	
			Prismatic crystals	92% CaO 5% SiO ₂	
		50 mm ²⁾	Needles	48% CaO 25% SO ₃ 20% Al ₂ O ₃ 5% SiO ₂	
			Small plates	60 % CaO 27% Al ₂ O ₃ 4% SiO ₂	
			Hexagonal plates	89% CaO 7% SiO ₂	
			Big plates	96% CaO 2% SiO ₂	

Comments from Kalinowski&Trägårdh (2011) are cited below.

1) δThe surface covered by small aggregate (bunches of size 10-20 µm) of needle-shaped crystals of Ca-Al-sulfate with ettringite composition. öGrains or crystals with rounded and irregular shape consisting of CaCO₃ (size 5-10 µm). öSingle aggregate of flat crystals of Ba-sulfate. Indications that these crystals have grown from one crack surface to the other.

2) δRelatively big (<300 µm) plate-shaped crystals of Ca(OH)₂. öAggregate of needle-shaped crystals of Ca-Al-sulfate with ettringite composition. öSmall flat and short prismatic crystals of CaCO₃. öNo Ba-sulfate.

Table 15.2: Element composition of precipitations in cracks.
Specimens cyclically exposed to sea water and drying.

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
55 mm	0.2 mm	5 mm ¹⁾	Micro-crystalline aggregate	92 % MgO 3 % SiO ₂ 2% CaO	H55-2-2-2 Fig A3.2
			Small prismatic crystals	53-58 % CaO 34% MgO 6-9 % SiO ₂	
		50 mm ²⁾	Needles	52% CaO 17-18% Al ₂ O ₃ 25-27% SO ₃	
			Hexagonal Crystals type 1	52 % CaO 27% SO ₃ 17% Al ₂ O ₃	
			Hexagonal Crystals type 2	96% CaO	
			Hexagonal and Prismatic crystals	93-96% CaO	
		0.4 mm	5 mm ³⁾	Short prismatic Crystals type 1	
	Short prismatic Crystals type 2			58-66% SiO ₂ 30-35% MgO 3-5% CaO	
	Needles			82-93% MgO 4-18% SiO ₂ 1-3% CaO	
	50 mm ⁴⁾		Microcrystalline aggregates	52-56% MgO 37-41% SiO ₂ 3% Al ₂ O ₃	
			Long, thin prisms	93-% CaO 4 % MgO	
			Small crystal aggregates	38-49% MgO 20-36% CaO 21-23% SiO ₂ 3-5% Al ₂ O ₃ 10-13% Cl ₂ O	
			Thin coatings	90% CaO 56-6% SiO ₂	

Comments from Kalinowski&Trägårdh (2011) are cited below.

- 1) δThe crack surface is covered by a mat of (probably) Mg(OH)₂. δSmall short prismatic crystals of Ca-Mg-oxide with Si-content up to 9%.
- 2) δBig amount of aggregates of needle-shaped crystals of Ca-Al-sulfate with ettringite composition. δBig amount of big plate-shaped crystals of Ca(OH)₂.
- 3) δThe crack surface is covered by a fine-crystalline mat of (probably) Mg(OH)₂. δSingle big short-prismatic crystals of Ca-Mg-carbonate and flat crystals of Mg-silicate.
- 4) δFine-crystalline mat of Mg-silicate. δBig amount of aggregate of long-prismatic crystals of CaCO₃.

*Table 15.3: Element composition of precipitations in cracks.
Specimens exposed to one-sided sea water suction.*

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
55 mm	0.2 mm	5 mm ¹⁾	Short prismatic crystals	92 % CaO 4 % SiO ₂	H55-2-3-2 Fig A3.3
			Severely cracked Cement paste	91 % CaO 4 % SiO ₂	
		25 mm ²⁾	Severely cracked Cement paste	45-53 % CaO 33-40 % SiO ₂	
	0.4 mm	5 mm ³⁾	Short rhombic crystals	92% CaO 2-5% SiO ₂	H55-4-3-2 Fig A3.3
			25 mm ⁴⁾	Severely cracked Cement paste	

Comments from Kalinowski&Trägårdh (2011) are cited below.

1) Relatively small amount of short-prismatic, cube-shaped crystals of Ca(OH)₂/CaCO₃.

2) Areas of mm-size with Si-, Na, and K-rich composition; probably alkali-silica-gel formed by reaction between pore solution and alkali-reactive aggregate.

3) Single mm-size areas with a small amount of small crystals of Ca(OH)₂/CaCO₃.

4) Heavily cracked area in the cement paste containing a Si-rich compound, probably consisting of alkali-silica gel.

*Table 15.4: Element composition of precipitations in cracks.
Specimens permanently exposed to tap water.*

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
55 mm	0.4 mm	5 mm ¹⁾	Crystal aggregate	88-92% CaO 5-7% SiO ₂	S155-4-1-2-R Fig A3.4
			Long prismatic crystals	96% CaO 1-2% SiO ₂	
		50 mm ²⁾	Needles	59% CaO 20% SO ₃ 14 % Al ₂ O ₃ 4% SiO ₂	
			Crystals	92-98% CaO 2-4% SiO ₂	

Comments from Kalinowski&Trägårdh (2011) are cited below.

1) Big amount of short- and long-prismatic crystals of CaCO₃. Size up to 0,4 mm. No Ca-Al-sulfate has been observed.

2) Big plate-shaped crystals of Ca(OH)₂/CaCO₃. A few crystal aggregates of Ca-Al-sulfate with ettringite composition.

Table 15.5: Element composition of precipitations in cracks.
Specimens permanently exposed to brackish water.

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
55 mm	0.4 mm	5 mm ¹⁾	Crystals and coatings	93-97% CaO 3-5% SiO ₂	S155-4-1-2-Ö Fig A3.5
			Needles	54% CaO 20-22% SO ₃ 15-18% Al ₂ O ₃ 6-9% SiO ₂	
			Small crystals	93% CaO 5% SiO ₂	
		50 mm ²⁾	Small flat crystals Type 1	48-54% CaO 29-40% Al ₂ O ₃ 10-18% Cl ₂ O	
			Small flat crystals Type 2	78% CaO 13-16% Cl ₂ O 5-7% Al ₂ O ₃	
			Needles	68% CaO 19% SO ₃ 10% Al ₂ O ₃	
			Big plates	98% CaO	

Comments from Kalinowski&Trägårdh (2011) are cited below.

1) Thin fine-crystalline coatings and single bigger crystal aggregates with irregular shape consisting of CaCO₃.

2) Aggregate of needle-shaped crystals consisting of Ca-Al-sulfate with ettringite composition. Short-prismatic crystals (size <40 µm) of CaCO₃. Long-prismatic crystals (<10 µm) of Ca(CO)₂.

15.4 Minerals in cracks – 28 month versus 1 year exposure

For specimens permanently immersed in sea-water, brackish water, or cyclic exposure to sea-water and drying, essentially the same type of precipitation is found after 2 years as after one year exposure, viz. CaCO₃, Ca(OH)₂ and Mg(OH)₂ crystals, and needle-like crystals of ettringite-like type, see Fagerlund&Hassanzadeh (2010).

Any differences, quantitatively, in the amount of precipitation after the different exposure times could not be detected by the technique used. Measurements of the chloride diffusion coefficient might give a qualitative answer.

In specimens exposed to water suction from the un-cracked side, there are indications of alkali-silica reaction after 2 years exposure, which is peculiar since, as far as is known, non-reactive aggregate was used. This type of exposure was not used for specimens exposed for one year.

15.5 Chloride concentration in crack walls

Thin slices were cut perpendicular to the crack walls on 4 depths in the crack (5-10 mm, 15-20 mm, 25-30 mm and 35-40 mm); see figure 15.1. The outer 5 mm from each slice was broken loose and used for chloride analysis.

Chloride profiles were also taken in a section about 3 centimetres beside the crack in order to see the difference between penetration in the bulk concrete and in the crack.

The chloride content was determined by ion selective electrode on dissolved sample. The cement content was determined by EDTA-titration using photometric determination of

transition. It is assumed that no other component in the sample but cement contains calcium and that the CaO content of the cement is 63 weight-%. The technique used gives the *total* chloride content, i.e. the sum of free and bound chloride.

According to the report by Kalinowski&Trägårdh (2011) the measurement uncertainty in chloride content is $\pm 0,1$ weight-% at a chloride content of 1 weight-%.

The results for exposure types 1 and 2 are shown in figure 15.7-15.10. In these figures comparisons are also made with the chloride profiles observed after 1 year exposure copied from report (1).

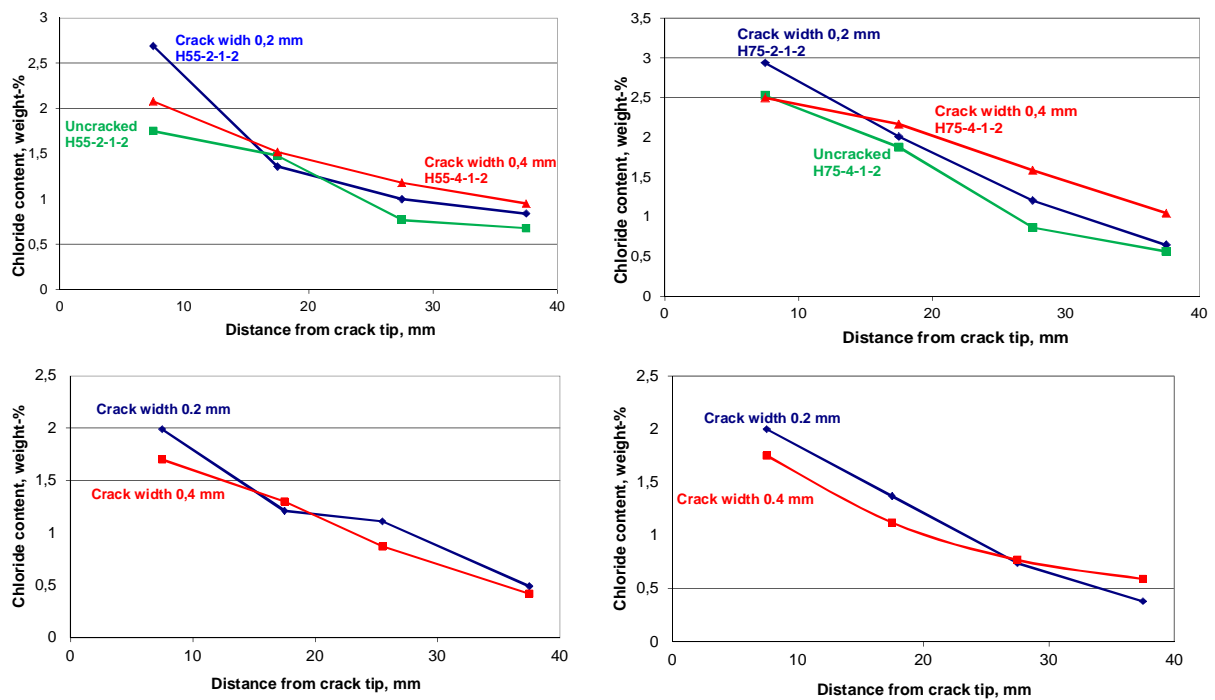


Figure 15.7: Chloride content in crack walls. Permanently immersed in sea-water.
 Upper row: 28 months exposure. Lower row: 1 year exposure.
 Left column: 55 mm cover. Right column: 75 mm cover.

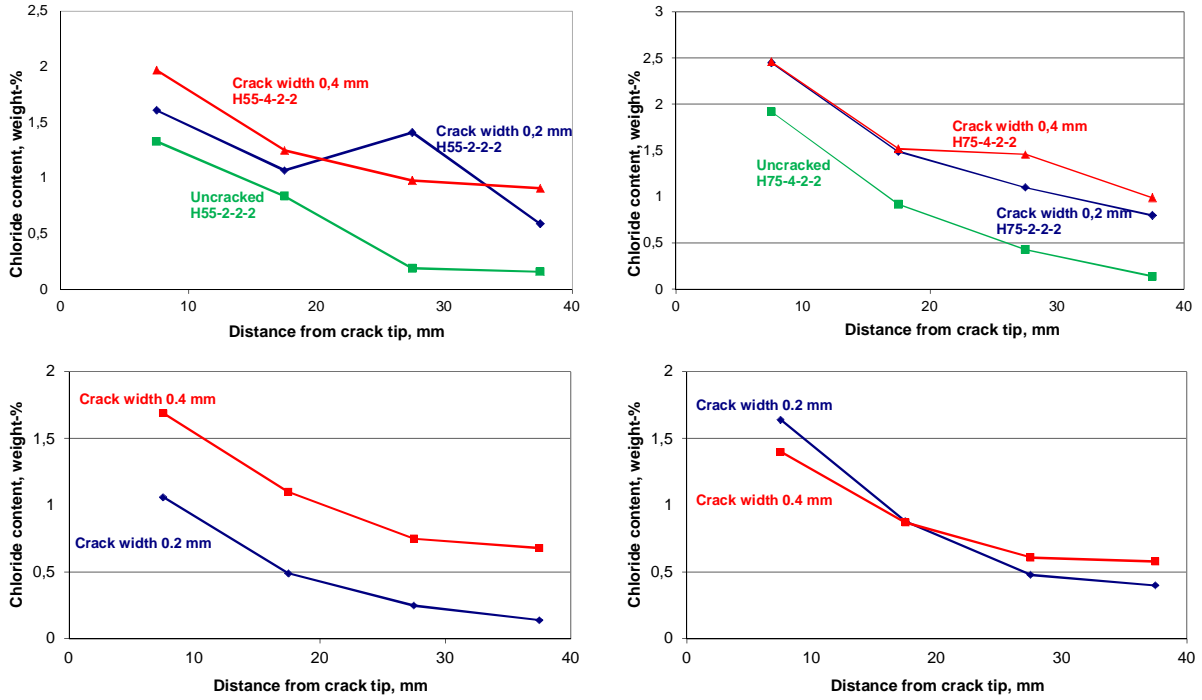


Figure 15.8: Chloride content in crack wall. Cyclic immersion and drying in sea-water. Upper row: 28 months exposure. Lower row: 1 year exposure. Left column: 55 mm cover. Right column: 75 mm cover.

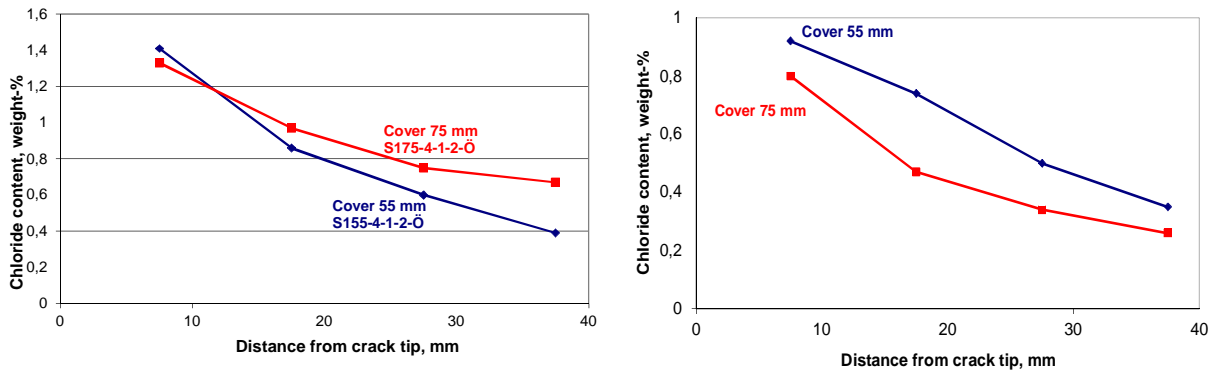


Figure 15.9: Chloride content in crack wall. Permanently immersed in brackish water. Effect of cover. Crack width 0,4 mm. Left: 28 month exposure. Right: 1 year exposure.

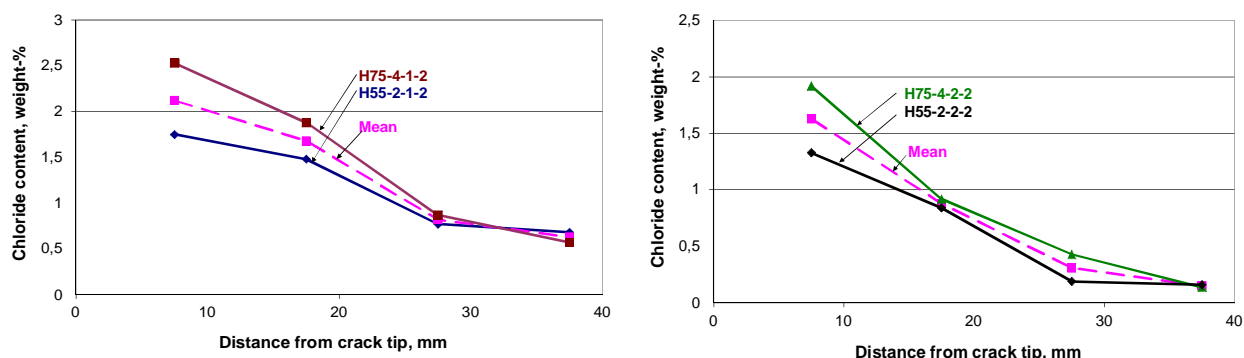


Figure 15.10: Chloride content in un-cracked concrete. 28 month exposure.
Left: Permanent in sea-water. Right: Cyclic in sea-water and drying.

The following observations are made:

1. *General observation*

- For all specimens, and both exposure times, the salt concentration in crack walls decreases with increasing distance from the crack tip. Since the crack widths are quite big, this shows that precipitation in cracks obstructs the inflow of chloride.

2. *Specimens permanently stored in sea-water (figure 15.7)*

- The chloride content in crack walls after 28 months exposure is about 2 to 3% on the depth 7.5 mm and about 0,6 to 1% on 37.5 mm depth. The chloride content is rather independent on the thickness of the cover.
- As expected, the chloride content in crack walls is higher after 28 months exposure than after 1 year.
- In its outer part the crack width 0.4 mm seems to give somewhat lower chloride content than 0.2 mm. On bigger depth the result is reverse.
- Concrete cover 75 mm gives somewhat higher chloride content in the outer part than 55 mm, despite the fact that the crack width is the same.
- Chloride penetration in cracks is somewhat higher than in bulk concrete.

3. *Cyclic immersion and drying in sea water (figure 15.8)*

- The chloride content on 7,5 mm depth is a bit lower than for permanent immersion; 1,5-2,5% compared with 2-3%. For bigger depth the difference is small.
- 28 month exposure gives higher chloride content than 1 year exposure.
- The chloride content on 35 mm depth reaches about the same level as permanent immersion; i.e. about 0,8-1%.

- As for permanent immersion, concrete cover 75 mm gives somewhat higher chloride content in the outer part than 55 mm cover.
 - Chloride penetration in cracks is much higher than in bulk concrete.
4. *Specimens permanently immersed in brackish water (figure 15.9)*
- 28 month exposure gives considerably higher chloride content than 1 year exposure.
 - As expected, the chloride content is lower than at immersion in sea water, 1,4% on 7,5 mm depth compared with 0,8% and 0,6% on 35 mm depth compared with 0,3%.
5. *Un-cracked specimens (figure 15.10)*
- Chloride penetration is always smaller in un-cracked concrete than in cracks.
 - Permanent immersion in se-water gives higher chloride penetration than cyclic immersion and drying.
6. *Specimens exposed to water suction from the un-cracked side*
 No chloride (<0,03%) could be detected in the crack which shows that the upper part of the concrete specimen had been so dry that chloride transport could not take place. This is illustrated by Figure 15.11.

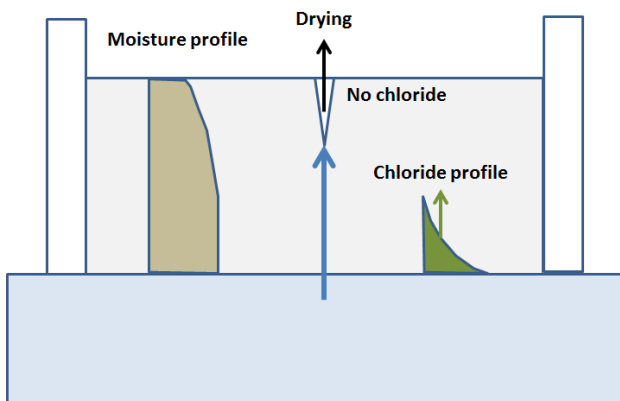


Figure 15.11: Exposure type 3. Moisture and chloride distribution, principally.

15.6 Chloride transport coefficient

Theoretically, the chloride profiles can be used for estimation of the chloride transport coefficient in cracks using the solution to Fick's law, Crank (1975):

$$\frac{c_x}{c_s} = \operatorname{erfc} \left[\frac{x}{(4 \cdot \delta \cdot t)^{1/2}} \right]$$

where

c_x is the total chloride content on depth x (m)

c_s is the total chloride content at the surface (crack mouth)

δ is the (effective) chloride diffusion coefficient (m^2/s)

t is the exposure time (s)

The equation is based on the assumption that chloride binding is linear; i.e. that there is a constant relation between bound chloride and chloride in pore water. Moreover, it can only be applied to specimens that have been stored permanently in water.

The equation implies that there is no time delay caused by penetration into the 5 mm thick samples taken from crack wall, and that the relation between free and bound chloride is constant over time and independent of the chloride content.

Unknown entities in the equation are the surface concentration, and the diffusion coefficient. Theoretically, these entities can be obtained by applying the equation to the measured chloride content on different depths.

The actual measurements give different values of surface concentration depending on which measurement points are used. Since the same concrete was used in all tests it is reasonable to assume that the surface concentration (sum of bound and free chloride) is the same for all specimens stored in the same way, during the same length of time. Therefore, instead of calculating the surface concentration from a number of measurements, two *assumed* surface concentrations are used at the evaluation. These surface concentrations are selected on basis of an extrapolation to the surface of the measurements. Since chloride binding might not be linear, the diffusion coefficient might vary, depending on which point on the curves is used.

The result of the application of Fick's law based on two assumed surface concentrations gives the diffusivities listed in tables 15.6 and 15.7.

Table 15.6: Chloride diffusion coefficient for penetration in cracks.
Permanent immersion in sea water.

Specimen	Crack width (mm)	Cover (mm)	Assumed surface concentration (%)	Depth used for Determination of diffusion coefficient (mm)	Diffusion coefficient $\cdot 10^{-12} \text{ m}^2/\text{s}$
H55-2-1-2 Fig 15.7	0,2	55	3,5	7,5 (5-10)	4,6
				17,5 (15-20)	2,8
				27,5 (25-30)	4,6
				37,5 (35-40)	7,1
			4,0	7,5 (5-10)	2,2
				17,5 (15-20)	2,4
				27,5 (25-30)	4,0
				37,5 (35-40)	6,3
Mean					4,2
H55-4-1-2 Fig 15.7	0,4	55	3,5	7,5 (5-10)	1,3
				17,5 (15-20)	3,4
				27,5 (25-30)	5,7
				37,5 (35-40)	8,0
			4,0	7,5 (5-10)	0,9
				17,5 (15-20)	2,7
				27,5 (25-30)	4,9
				37,5 (35-40)	7,1
Mean					4,3
H75-2-1-2 Fig 15.7	0,2	75	3,5	7,5 (5-10)	9,3
				17,5 (15-20)	6,8
				27,5 (25-30)	5,8
				37,5 (35-40)	5,5
			4,0	7,5 (5-10)	3,4
				17,5 (15-20)	4,7
				27,5 (25-30)	4,9
				37,5 (35-40)	5,0
Mean					5,5
H75-4-1-2 Fig 15.7	0,4	75	3,5	7,5 (5-10)	2,8
				17,5 (15-20)	8,7
				27,5 (25-30)	9,3
				37,5 (35-40)	9,1
			4,0	7,5 (5-10)	1,6
				17,5 (15-20)	5,7
				27,5 (25-30)	7,3
				37,5 (35-40)	7,8
Mean					6,5
Uncracked H55-2-1-2 and H75-2-1-2 Mean curve Fig 15.10	No crack	55 and 75	3,5	7,5 (5-10)	1,5
				17,5 (15-20)	4,2
				27,5 (25-30)	1,5
				37,5 (35-40)	5,4
			4,0	7,5 (5-10)	1,1
				17,5 (15-20)	3,3
				27,5 (25-30)	3,2
				37,5 (35-40)	5,0
Mean					3,2

Table 15.7: Chloride diffusion coefficient for penetration in cracks.
Permanent immersion in brackish water.

Specimen	Crack width (mm)	Cover (mm)	Assumed surface concentration (%)	Depth used for determination of diffusion coefficient (mm)	Diffusion coefficient $\cdot 10^{-12}$ (m ² /s)
S155-4-1-2-Ö Fig 15.10	0.4	55	2,0	7,5 (5-10)	2,8
				17,5 (15-20)	3,4
				27,5 (25-30)	4,9
				37,5 (35-40)	5,8
			2,5	7,5 (5-10)	1,1
				17,5 (15-20)	2,3
				27,5 (25-30)	3,8
				37,5 (35-40)	4,8
			Mean		3,6
S175-4-1-2-Ö Fig 15.10	0.4	75	2,0	7,5 (5-10)	1,5
				17,5 (15-20)	4,1
				27,5 (25-30)	6,6
				37,5 (35-40)	11,0
			2,5	7,5 (5-10)	1,0
				17,5 (15-20)	2,9
				27,5 (25-30)	4,9
				37,5 (35-40)	8,0
			Mean		5,0

The diffusivity differs depending on which surface concentration is assumed; normally the highest of the two assumed concentrations give the lowest diffusivity. Besides the calculated diffusivity depends on which measurement point is used, which might depend on the following factors, (i) the location where the sample was extracted might not be the same as used in the analysis, the difference can be at least ± 5 mm, (ii) uncertainty in the chloride analysis.

The following conclusions can be drawn:

- For concrete cover 55 mm and storage in sea-water, the diffusivity in 0,2 mm and 0,4 mm wide cracks is only somewhat higher than in un-cracked concrete; $4,3 \cdot 10^{-12}$ m²/s compared with $3,2 \cdot 10^{-12}$ m²/s. For storage in brackish water the diffusivity in crack with width 0,4 mm is almost the same as in un-cracked concrete; $3,6 \cdot 10^{-12}$ compared with $3,2 \cdot 10^{-12}$ m²/s.
- This means that cracks with width 0,4 mm do not seem more dangerous with regard to reinforcement corrosion than the normally accepted crack width 0,2 mm. If 0,4 mm cracks are accepted the amount of reinforcement used for limiting crack width might be reduced which will substantially reduce the building cost.
- Cracks in concrete cover 75 mm gives somewhat higher diffusivity than the same cracks in cover 55 mm; $5,5 \cdot 10^{-12}$ to $6,5 \cdot 10^{-12}$ m²/s compared with $4,3 \cdot 10^{-12}$ m²/s in sea water and $5,0 \cdot 10^{-12}$ m²/s compared with $3,6 \cdot 10^{-12}$ m²/s in brackish water .
- The diffusivity in brackish water is somewhat lower than that in sea-water. Logically it should be the same if chloride binding is linear and the same amount of precipitation is present. The reason can be that the wrong surface concentration was used. As seen in the table the assumed surface concentration 2,0% gives diffusivities that are closer to the sea-water diffusivities than the value 2,5%.

The chloride diffusivity in cracks is lower after 28 month exposure than after 1 year exposure, see Table 15.8. This is probably an effect of continued healing of the cracks.

Table 15.8: Effect of exposure time on the chloride diffusivity.

Type of exposure	Crack width, mm	Chloride diffusivity · 10 ⁻¹² m ² /s	
		1 year	28 months
Immersion in sea-water	0,2	10,4	4,2
	0,4	9,4	4,3
Immersion in brackish water	0,4	6,0-9,8	3,6-5,0

REFERENCES

Kalinowski, M., Trägårdh, J. (2011): *Analys av utfällningar på sprickytor och kloridhalter i betong (Analysis of precipitations on crack surfaces and chloride content in concrete)*. Cement and Concrete Research Institute. Uppdragsnummer PX00644

Fagerlund, G., Hassanzadeh, M. (2010): *Self-healing of cracks in concrete long-term exposed to different types of water. Results after 1 year exposure*. Div. Building Research, Lund Institute of technology, Report TVBM-3156.

Crank, J. (1975): *The mathematics of diffusion*. Oxford University Press.

APPENDIX 1

Photographs of the lowest part of the crack before exposure and after 28 month exposure

I:Specimens exposed to sea water from the Swedish west coast
I.1:Specimens permanently immersed in sea water

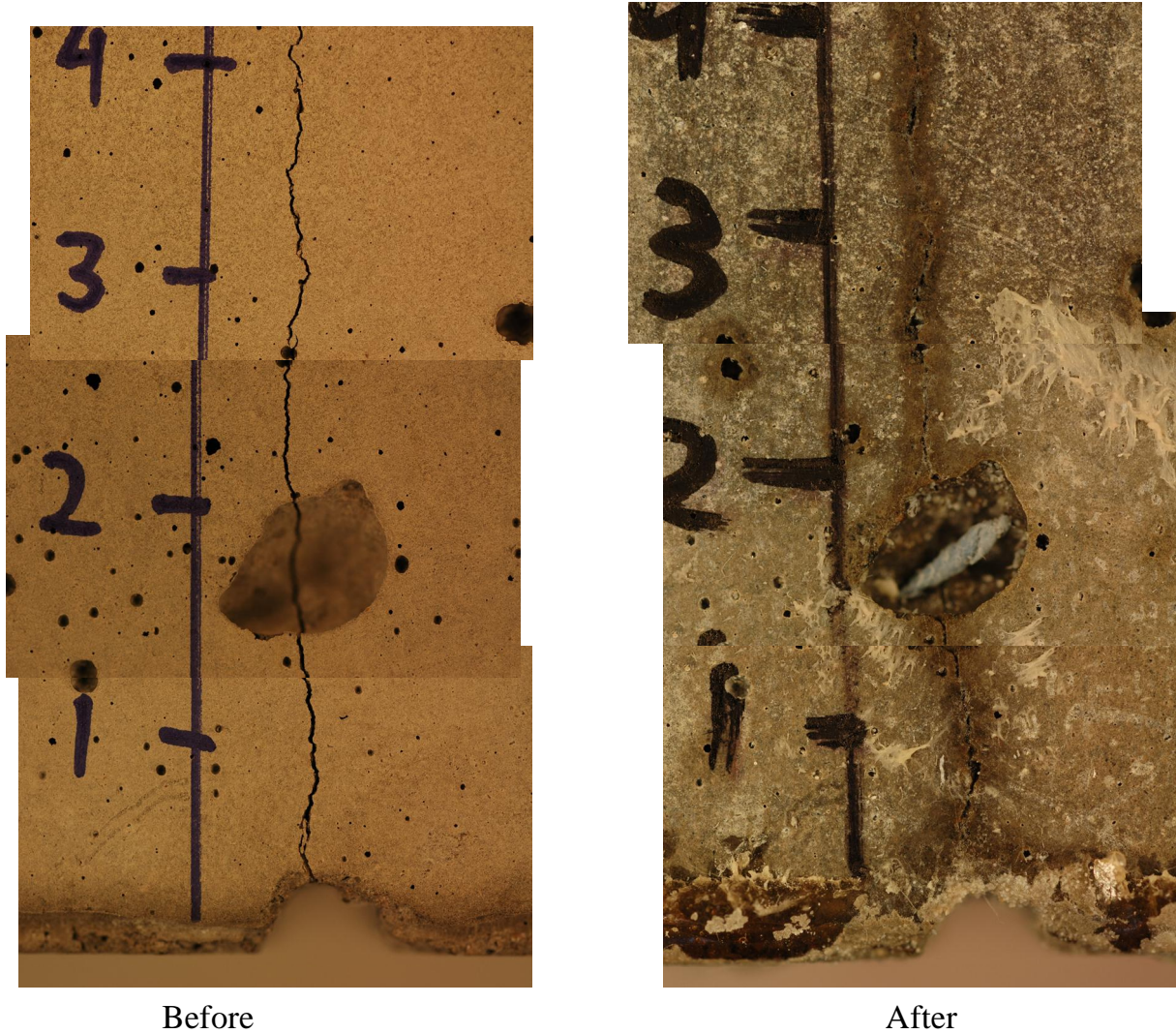
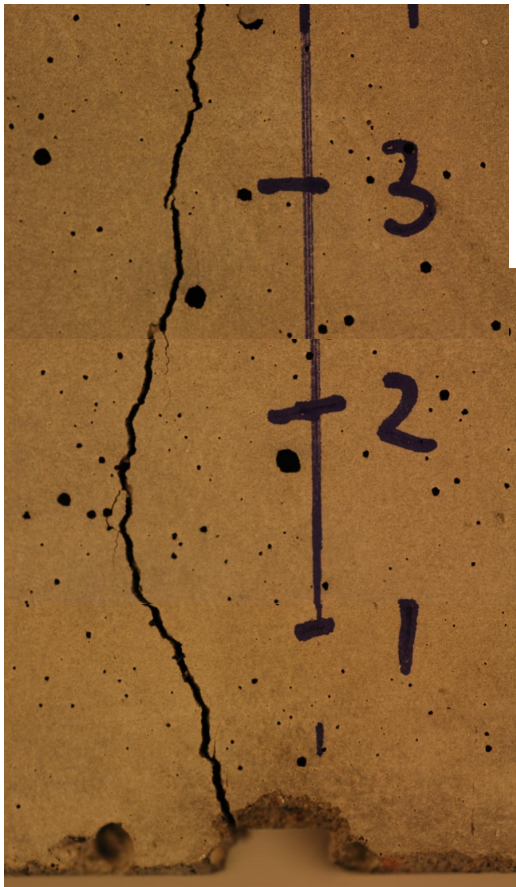
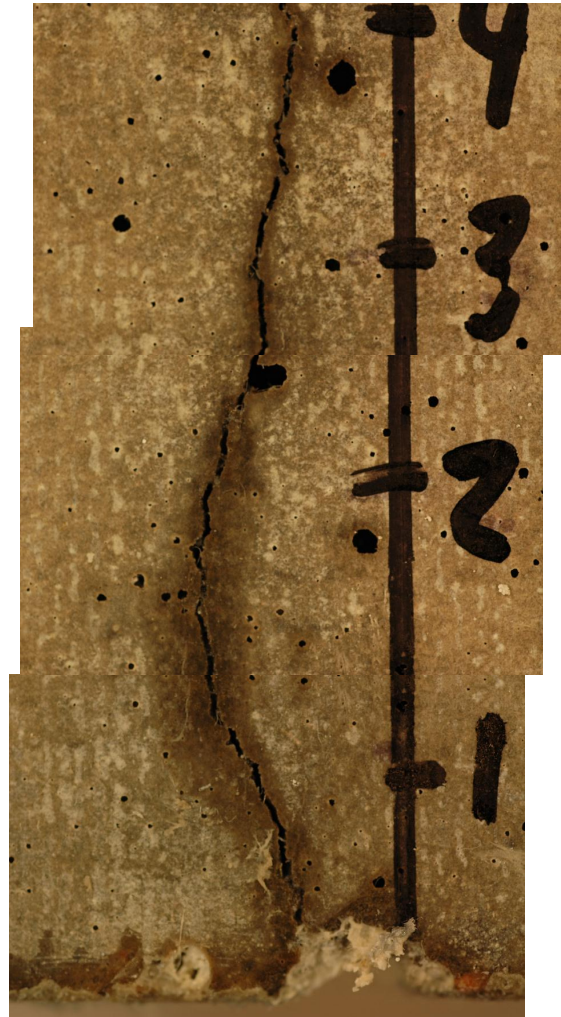


Figure A1.1: Permanently in sea water.

Crack width 0.2 mm. Cover 75 mm. Specimen H75-2-1-2

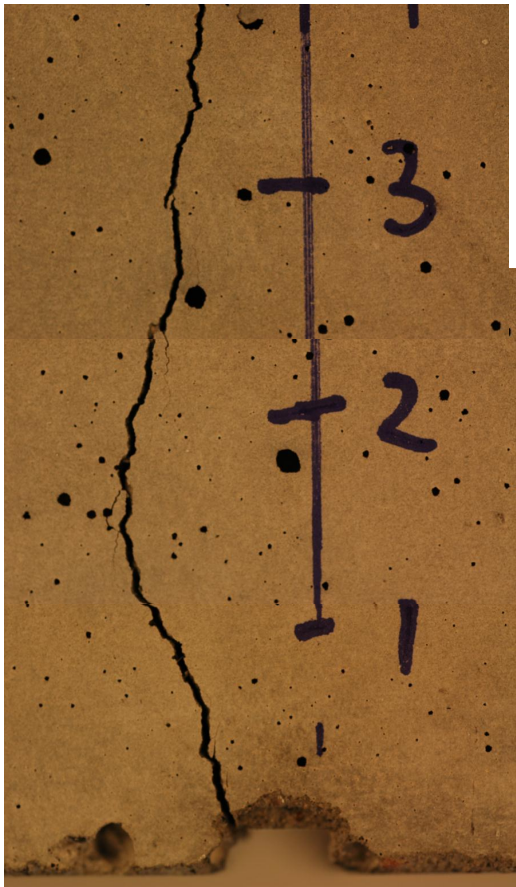


Before

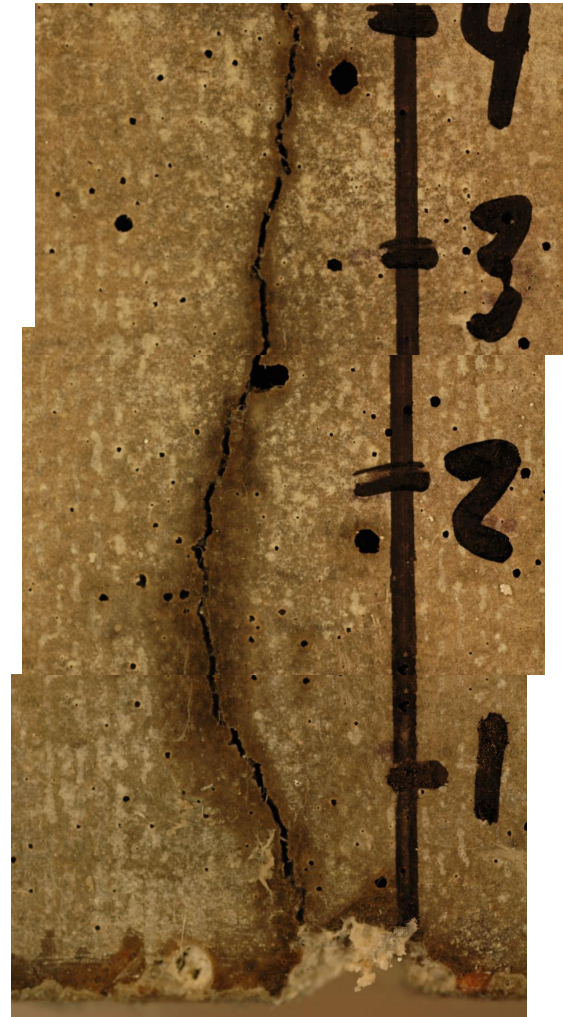


After

*Figure A1.2: Permanently in sea water.
Crack width 0.4 mm. Cover 75 mm. Specimen H75-4-1-2*



Before



After

*Figure A1.3: Permanently in sea water.
Crack width 0.2 mm. Cover 55 mm. Specimen H55-2-1-2*

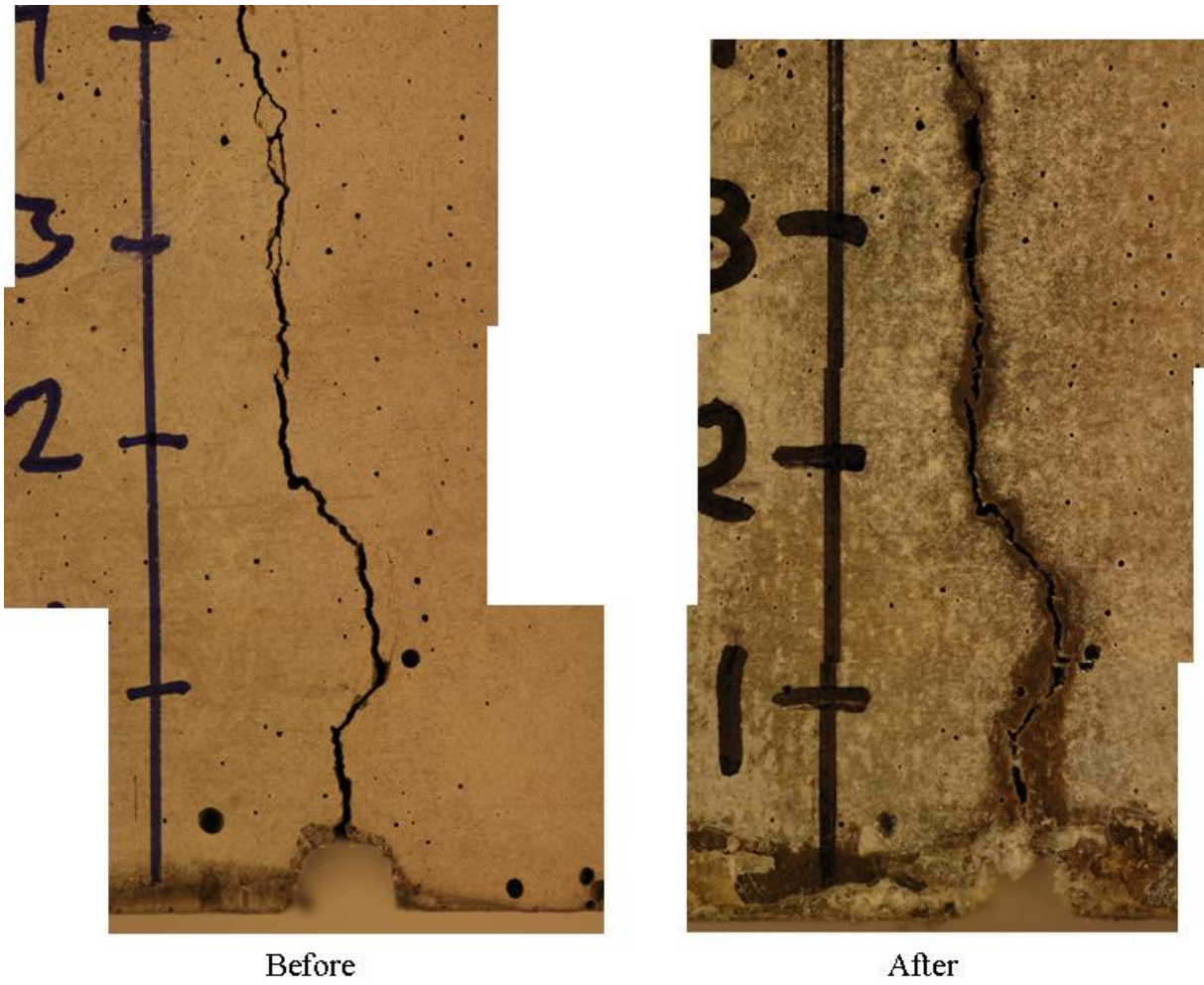


Figure A1.4: Permanently in sea water.

Crack width 0.4 mm. Cover 55 mm. Specimen H55-4-1-2

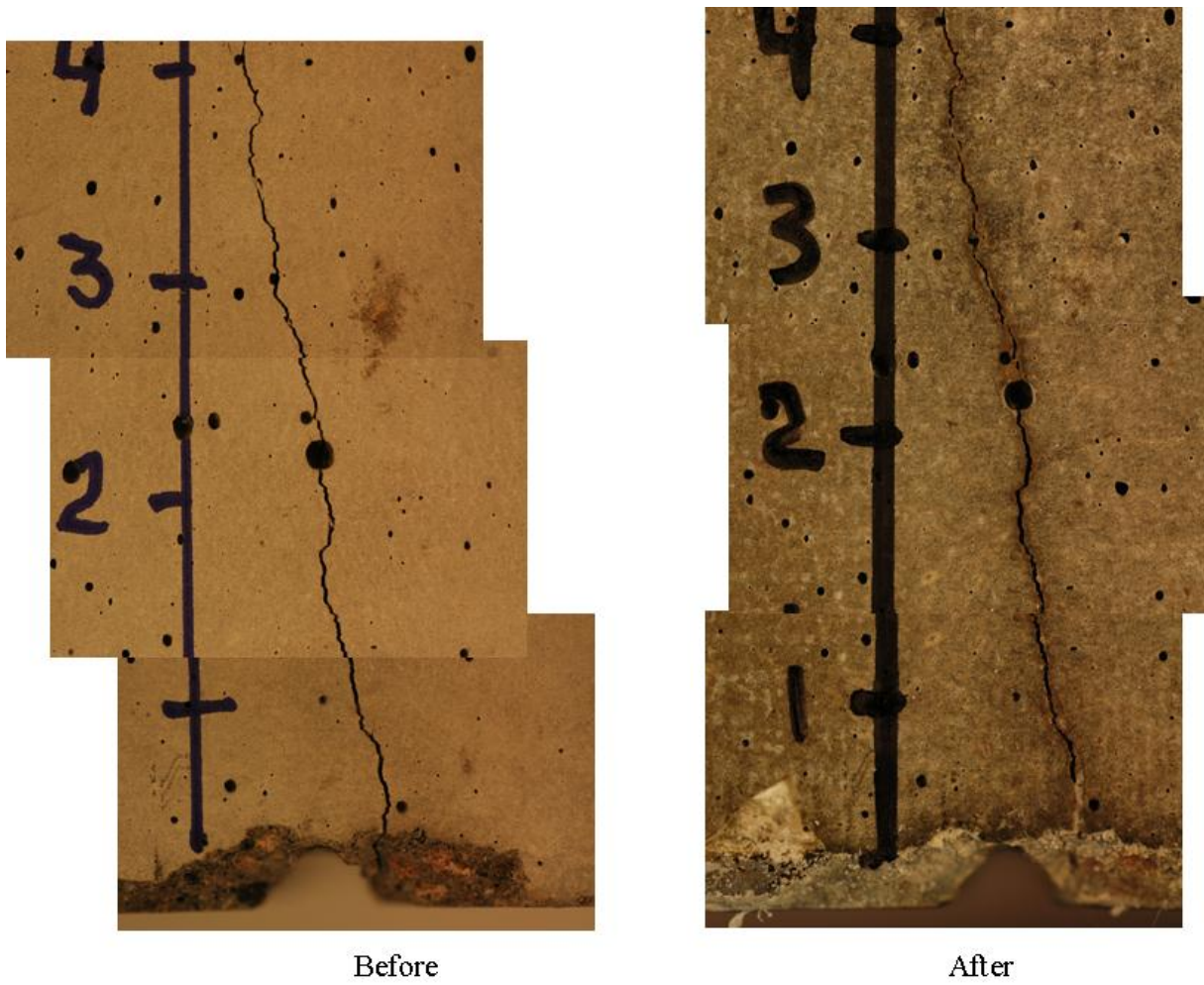
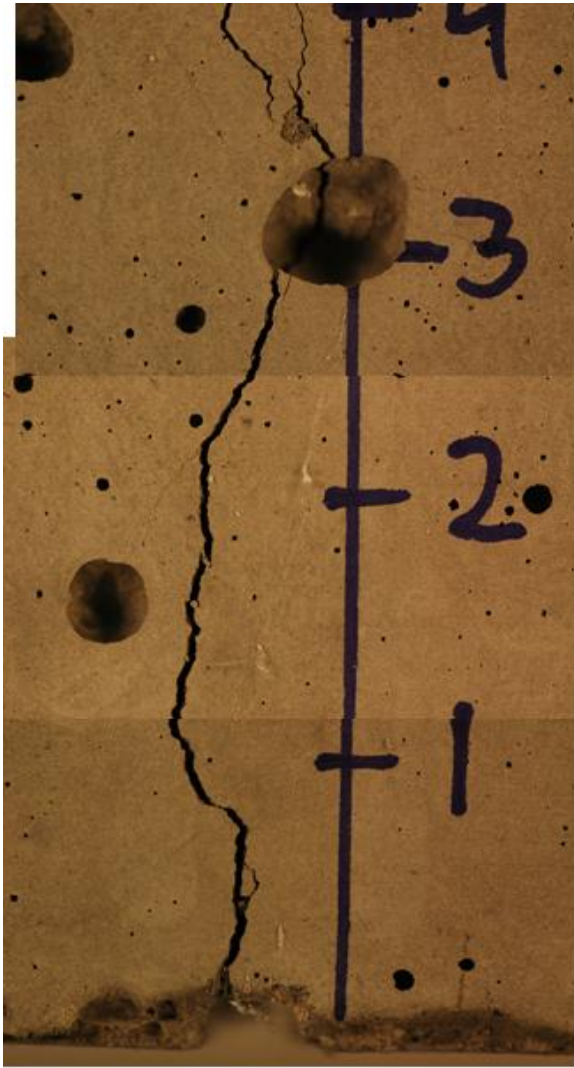
I.2: Specimens exposed to cyclic immersion in sea water and drying

Figure A1.5: Cyclic immersion in sea water and drying.

Crack width 0.2 mm. Cover 75 mm. Specimen H75-2-2-2



Before



After

*Figure A1.6: Cyclic immersion in sea water and drying.
Crack width 0.4 mm. Cover 75 mm. Specimen H75-4-2-2*



Before



After

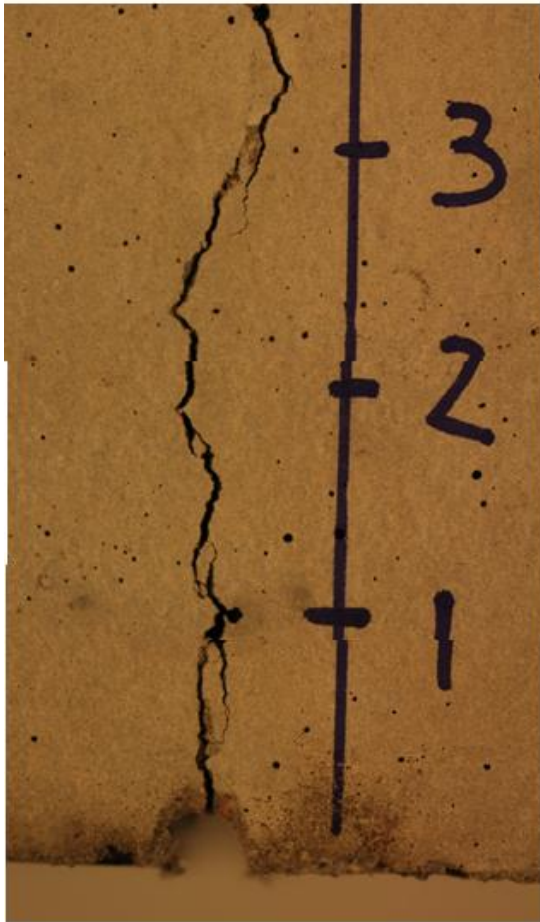
*Figure A1.7: Cyclic immersion in sea water and drying.
Crack width 0.2 mm. Cover 55 mm. Specimen H55-2-2-2*



*Figure A1.8: Cyclic immersion in sea water and drying.
Crack width 0.4 mm. Cover 55 mm. Specimen H55-4-2-2*

I.3: Specimens exposed to water suction from the un-cracked side

*Figure A1.9: Water suction from the un-cracked side.
Crack width 0.2 mm. Cover 75 mm. Specimen H75-2-3-2*

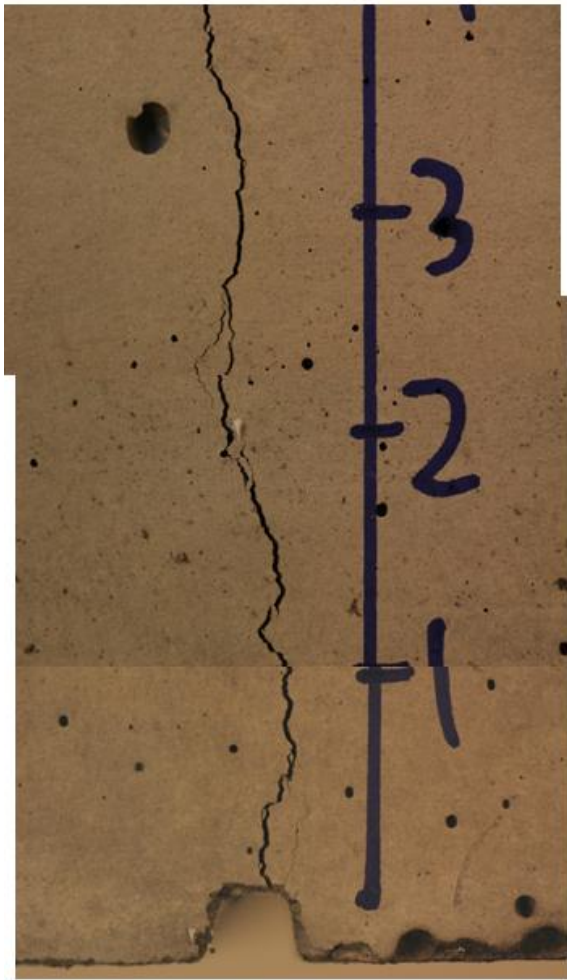


Before



After

*Figure A1.10: Water suction from the un-cracked side.
Crack width 0.4 mm. Cover 75 mm. Specimen H75-4-3-2*



Before



After

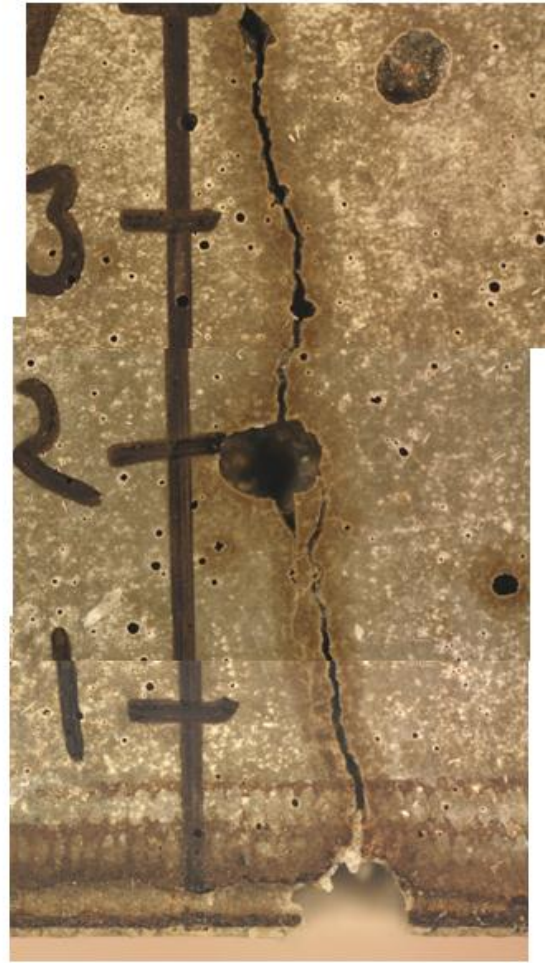
*Figure A1.11: Water suction from the un-cracked side.
Crack width 0.2 mm. Cover 55 mm. Specimen H55-2-3-2*



*Figure A1.12: Water suction from the un-cracked side.
Crack width 0.4 mm. Cover 55 mm. Specimen H55-4-3-2*

II: Specimens permanently immersed in brackish water from the Baltic Sea

Before



After

*Figure A1.13: Permanently in brackish water.
Crack width 0.4 mm. Cover 75 mm. Specimen S175-4-1-2Ö*



Before



After

*Figure A1.14: Permanently in brackish water.
Crack width 0.4 mm. Cover 55 mm. Specimen S155-4-1-2Ö*

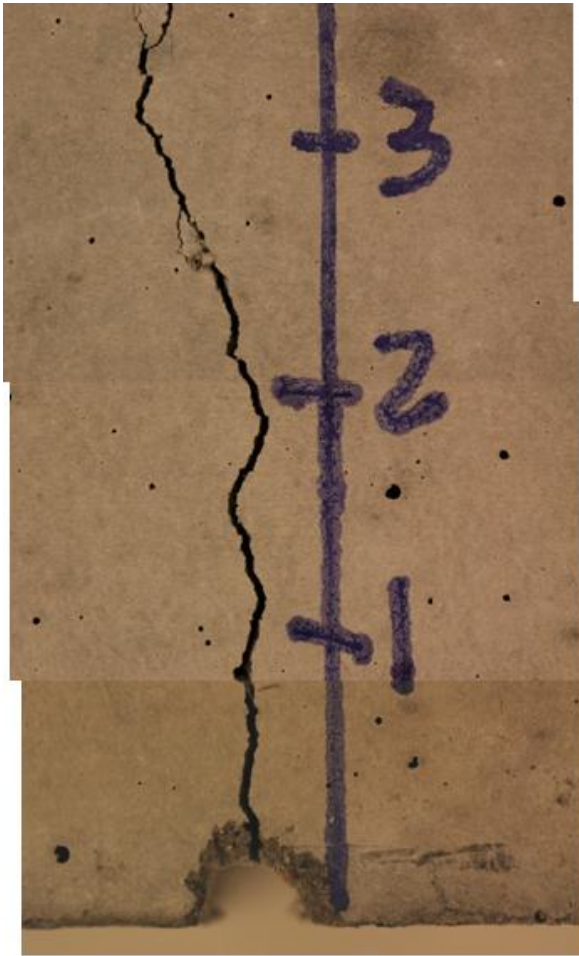
III: Specimens permanently immersed in pure water

Before



After

*Figure A1.15: Permanently in pure water.**Crack width 0.4 mm. Cover 75 mm. Specimen S175-4-1-2R*



Before



After

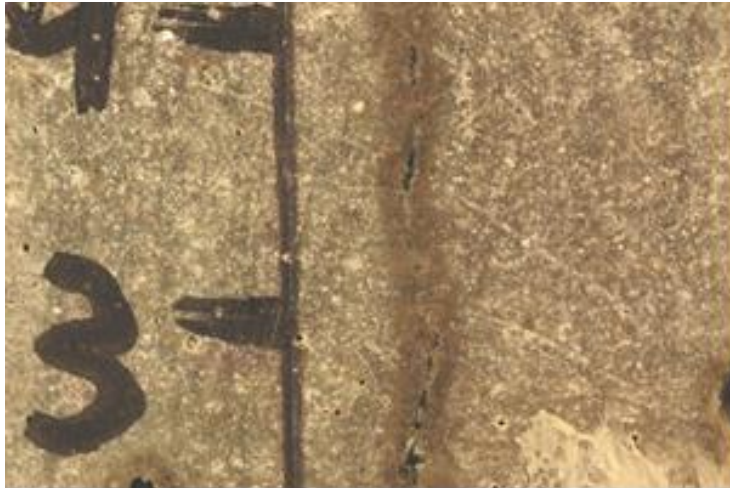
Figure A1.16: Permanently in sea water.

Crack width 0.4 mm. Cover 55 mm. Specimen S155-4-1-2R

APPENDIX 2

Photographs of the crack on about 3 cm depth Before exposure and after 28 month exposure

Photographs of the lowest part of the crack (0-1 cm) of the same specimens after 28 month exposure are shown in Figure 12.2 to 12.7 in the main text



Permanent immersion
H75-2-1-2

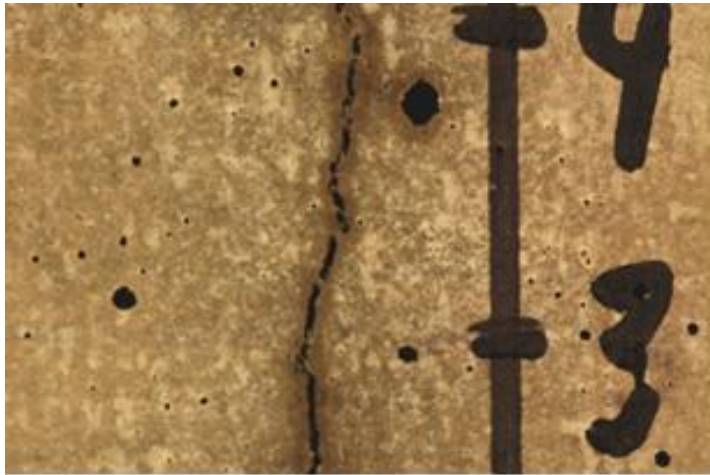


Cyclic immersion
H75-2-2-2

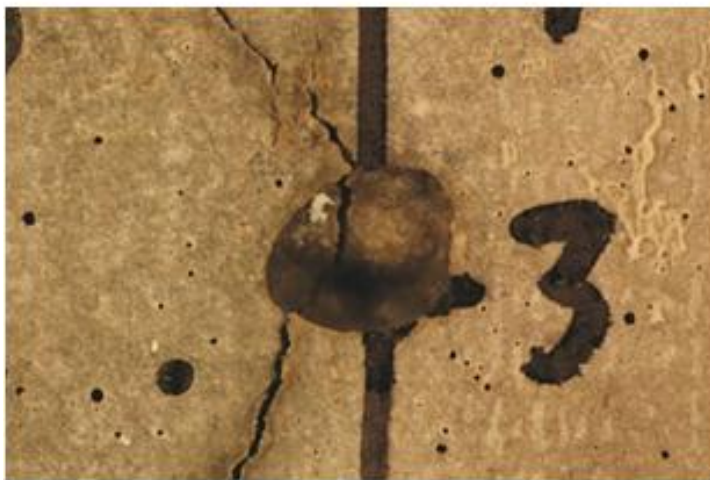


Water suction from the
un-cracked side
H75-2-3-2

Figure A2.1: 0.2 mm crack width, 75 mm cover. Exposure to sea water.



Permanent immersion
H75-4-1-2

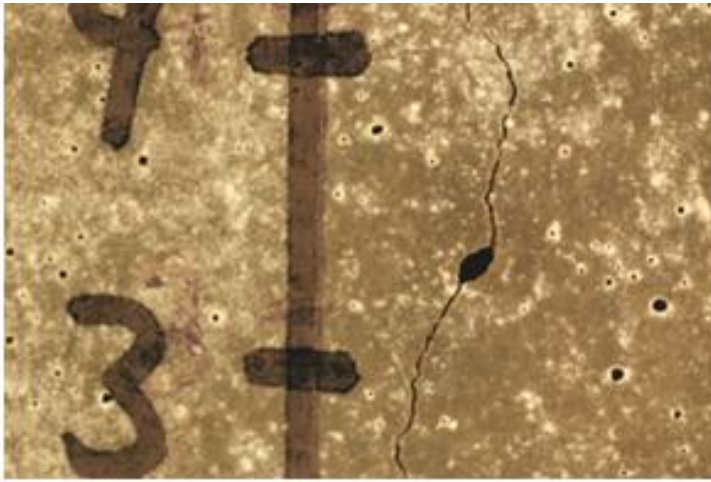


Cyclic immersion
H75-4-2-2

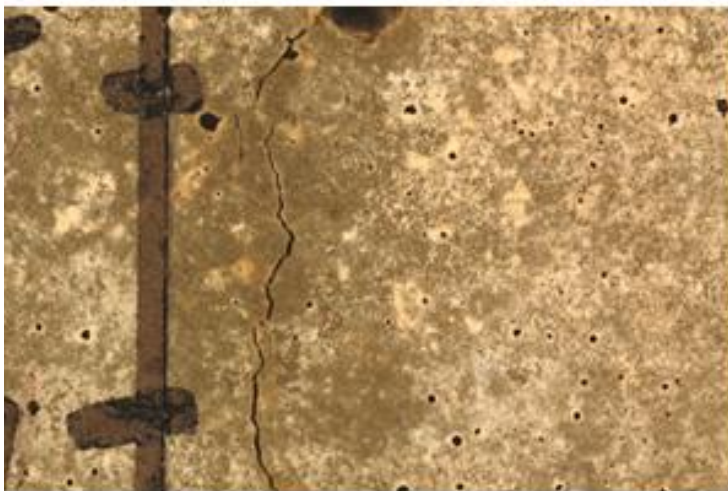


Water suction from the
un-cracked side
H75-4-3-2

Figure A2.2: 0.4 mm crack width. 75 mm cover. Exposure to sea water.



Permanent immersion
H55-2-1-2



Cyclic immersion
H55-2-2-2



Water suction from the
un-cracked side
H55-2-3-2

Figure A2.3: 0.2 mm crack width. 55 mm cover. Exposure to sea water.



Permanent immersion
H55-4-1-2

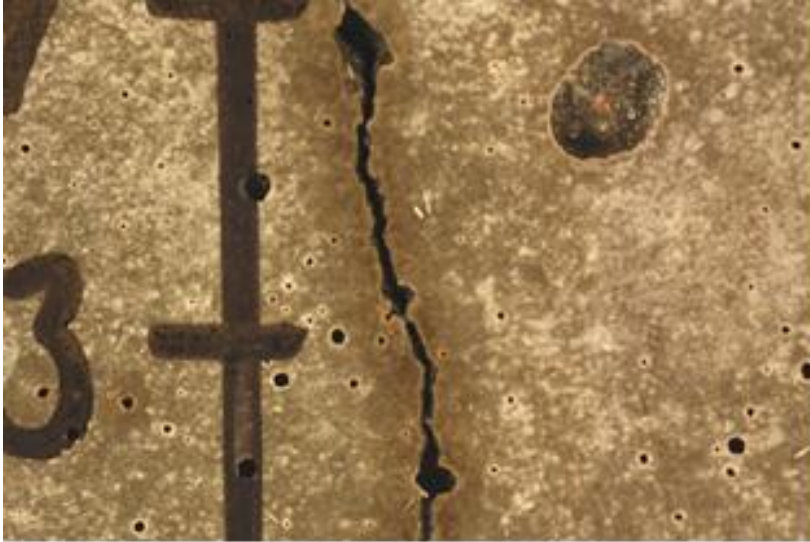


Cyclic immersion
H55-4-2-2

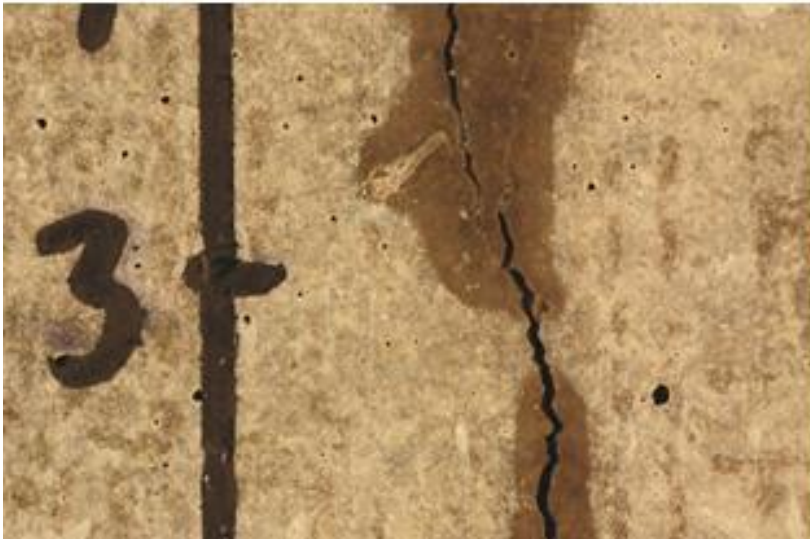


Water suction from the
un-cracked side
H55-4-3-2

Figure A2.4: 0.4 mm crack width. 55 mm cover. Exposure to sea water.



Permanent immersion
S175-4-1-2-Ö



Permanent immersion
S155-4-1-2-Ö

*Figure A2.5: 0.4 mm crack width. Exposure to brackish water.
Upper: 75 mm cover. Lower: 55 mm cover.*



Permanent immersion
S175-4-1-2-R



Permanent immersion
S155-4-1-2-R

*Figure A2.6: 0.4 mm crack width. Exposure to pure water.
Upper: 75 mm cover. Lower: 55 mm cover.*

APPENDIX 3

Micro-photographs of precipitations in cracks

From Kalinowski&Trägårdh (2011)

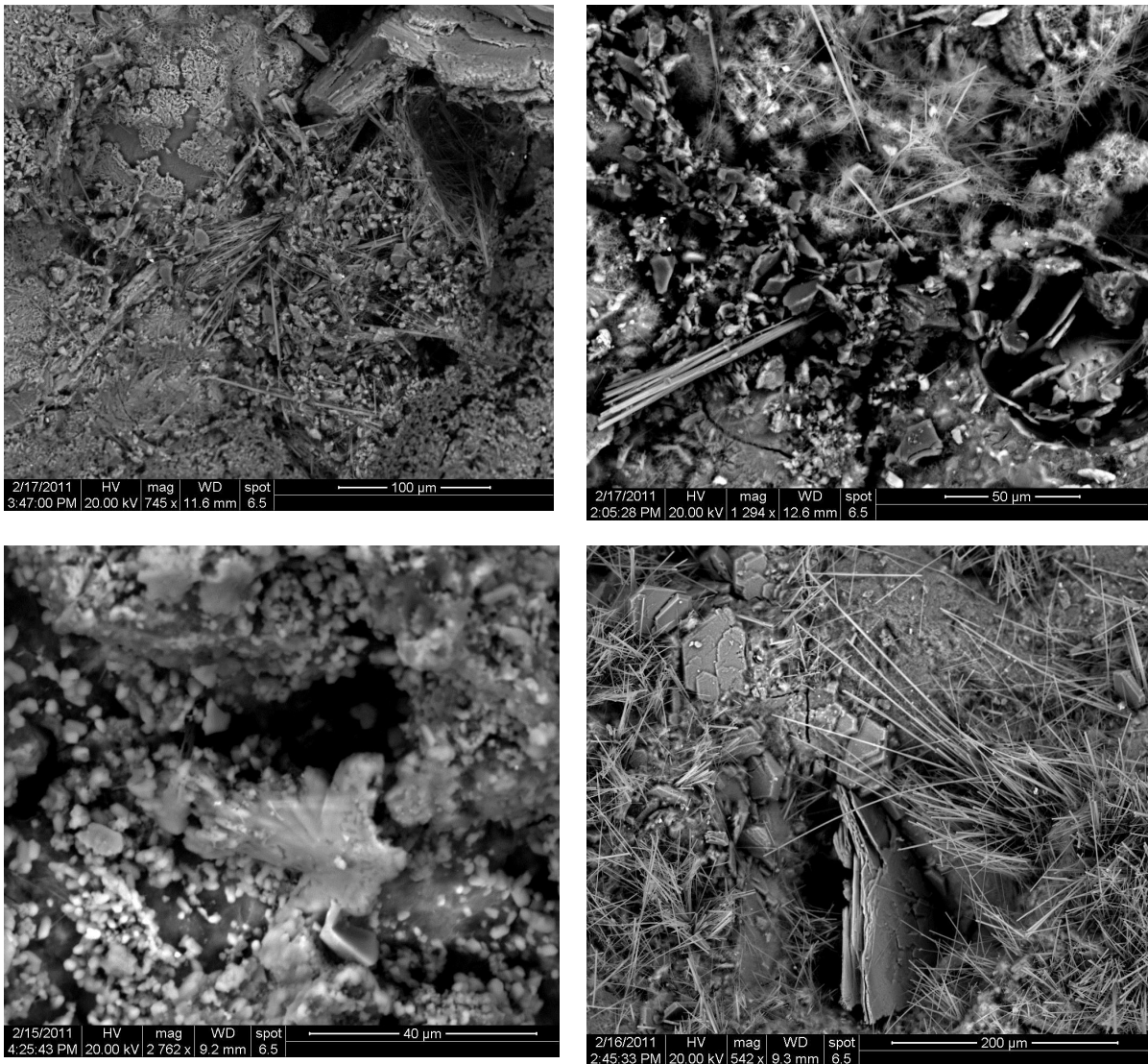


Figure A3.1: Specimens stored permanently in sea water. Cover 55 mm.

Left column: 5 mm from crack mouth.

Right column: 50 mm from crack mouth.

Upper row: Crack width 0.2 mm; Specimen H55-2-1-2.

Lower row: Crack width 0.4 mm; Specimen H55-4-1-2.

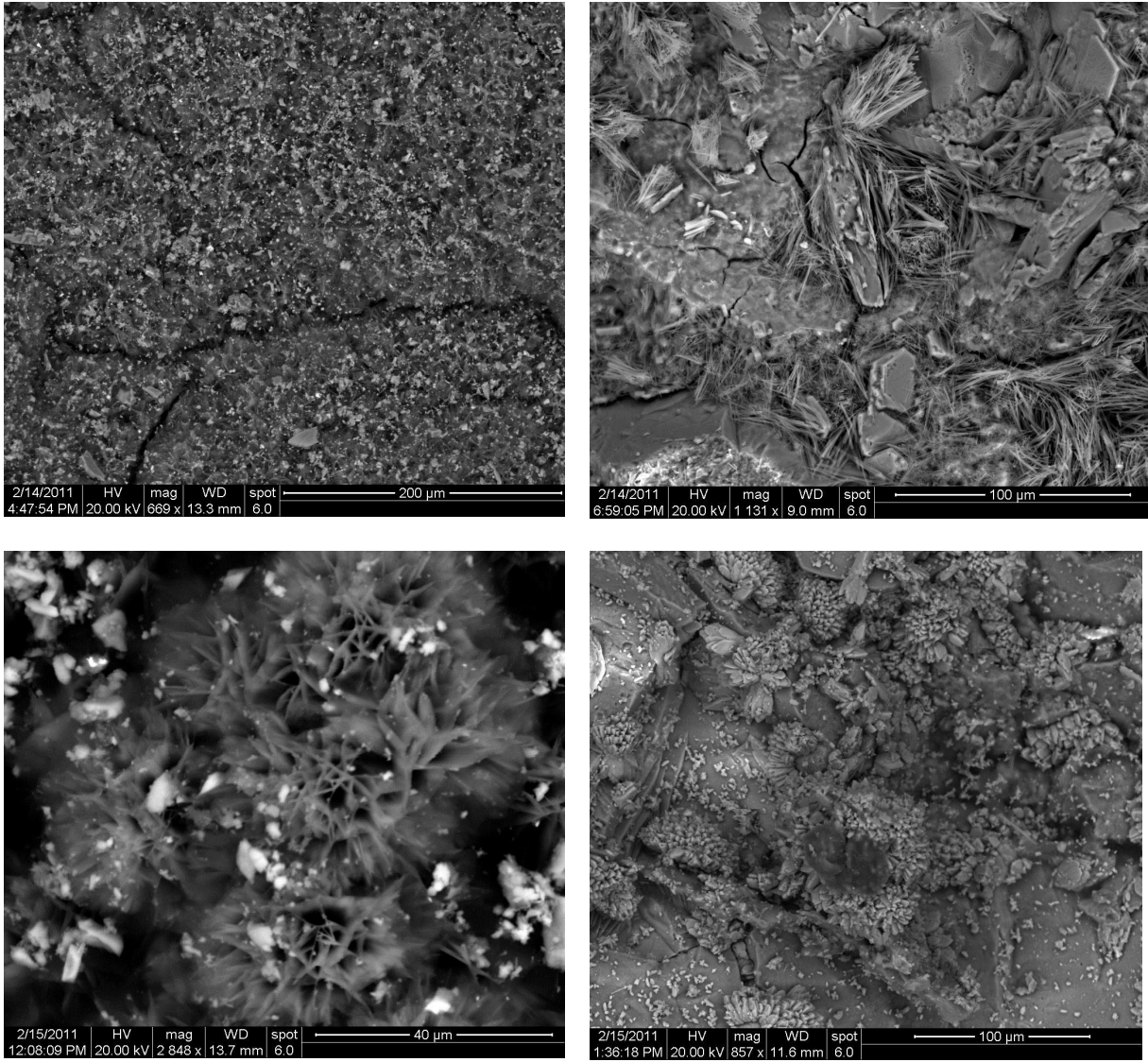


Figure A3.2: Specimens cyclically exposed to sea water and drying. Cover 55 mm.

Left column: 5 mm from crack mouth.

Right column: 50 mm from crack mouth.

Upper row: Crack width 0.2 mm; Specimen H55-2-2-2.

Lower row: Crack width 0.4 mm; Specimen H55-4-2-2.

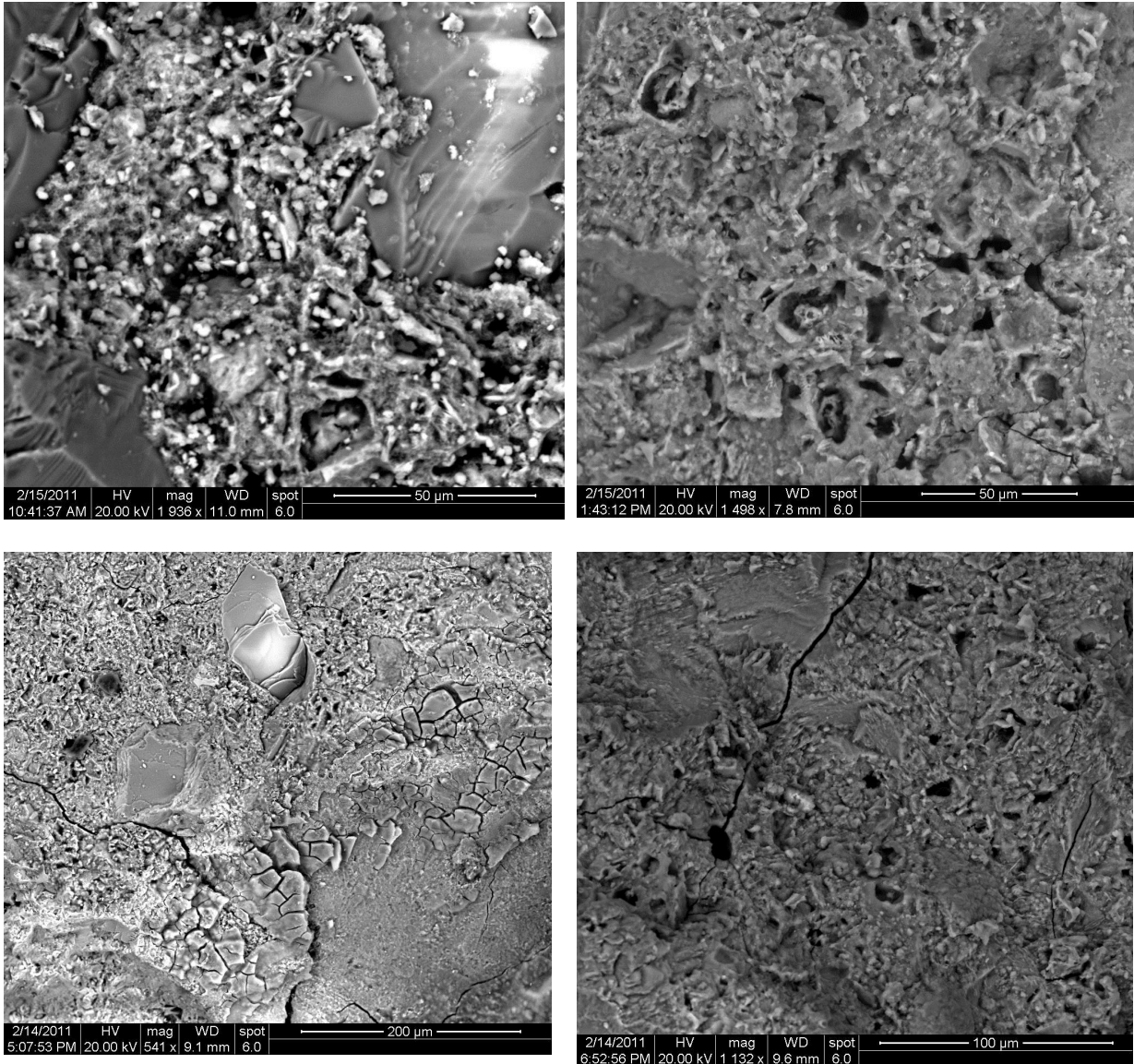


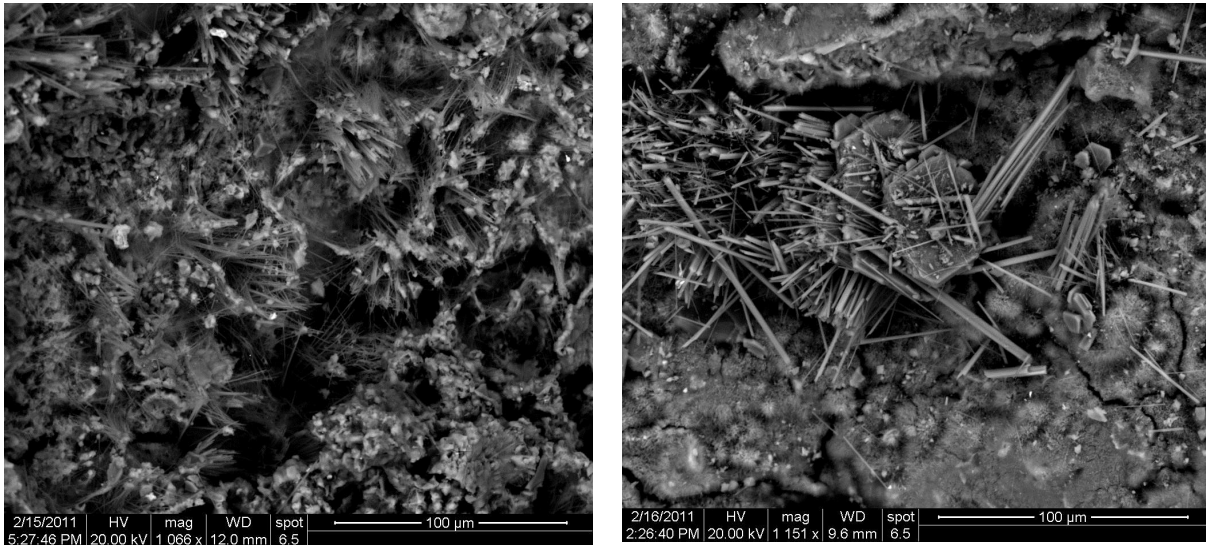
Figure A3.3: Specimens exposed to water suction from the un-cracked side. Cover 55 mm.

Left column: 5 mm from crack mouth.

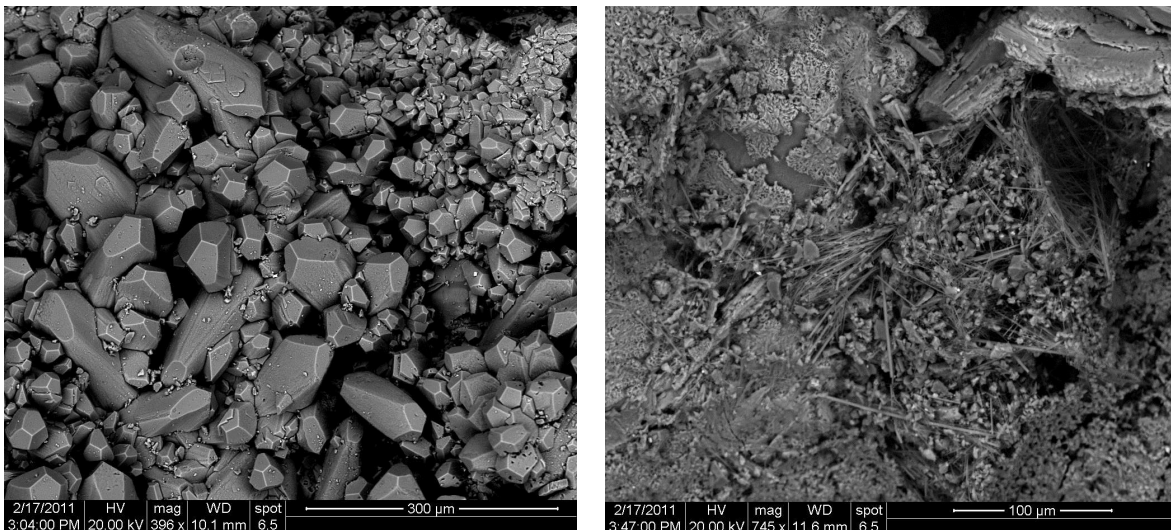
Right column: 50 mm from crack mouth.

Upper row: Crack width 0.2 mm; Specimen H55-2-3-2.

Lower row: Crack width 0.4 mm; Specimen H55-4-3-2.



*Figure A3.4: Specimens stored permanently in brackish water. Cover 55 mm.
 Left column: 5 mm from crack mouth.
 Right column: 50 mm from crack mouth.
 Crack width 0.4 mm; Specimen S155-4-1-2-Ö.*



*Figure A3.5: Specimens stored permanently in pure water. Cover 55 mm.
 Left column: 5 mm from crack mouth.
 Right column: 50 mm from crack mouth.
 Crack width 0.4 mm; Specimen S155-4-1-2-R.*