LUND INSTITUTE OF TECHNOLOGY
LUND UNIVERSITY

Division of Building Materials

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

Results after 1 year exposure

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FOREWORD

It has been known for long that concrete has a certain possibility to heal defects like cracks that appear during production or during service. Early studies showed that considerable restoration of strength can occur also in severely cracked concrete specimens. However, just as important, or even more important, is the potential ability of concrete to heal and thereby seal cracks from ingress of chloride ions.

In concrete rules of today the restrictions as regards crack width are strict for concrete exposed to sea water or de-icing salt. Often the maximum allowed crack is only 0.2 mm or even smaller. In order to cope with these requirements a large amount of reinforcement serving as crack distributor is often needed which causes big costs.

A research project was proposed with the aim of investigating to what extent healing of cracks of different width and at different concrete cover can occur in normal Swedish concrete exposed to different types of water; salt, brackish and pure. Funding was granted by the *Development Fund of the Swedish Construction Industry (SBUF)*, *Vattenfall Research and Development AB* and *SKANSKA Project Support AB*. We are grateful for their support.

The project is divided in two parts:

- Part 1: Exposure during 1 year before analysis of healing
- Part 2: Exposure during 2 years before analysis of healing

This report presents the results of Part 1.

Planning of the practical parts of the exposure tests in our laboratory and execution of these tests were performed by our colleagues Bo Johansson and Bengt Nilsson. We thank them for their interest in and contributions to the project.

Analyses of mineral components precipitated in the cracks and analyses of chloride ingress in the cracks were performed at the Swedish Cement and Concrete Institute in Stockholm by Mariusz Kalinowski and Leif Fjällberg. We thank them for fine work.

Lund, November 2010

Göran Fagerlund Manouchehr Hassanzadeh

CONTENT

SUMMARY

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

18 concrete specimens with induced cracks, 0.2 and 0.4 mm wide, were exposed to sea water, brackish water and tap water for 1 year. For most specimens the crack width has been locked mechanically. For four specimens the crack had the possibility to relax.

Two types of water exposure have been used:

- Permanent immersion
- Cyclic immersion and drying in lab air

Photographs were taken of the crack before and after exposure. Photos are shown in APPENDIX 1 and 2. The photographs indicate that some healing has occurred, particularly for specimens permanently immersed in sea water. The effect of relaxation seems to be marginal.

After terminated exposure the chloride content in the crack walls on different depths was determined. The chloride content diminishes with the crack depth which indicates that the precipitation of minerals in the crack has the ability to somewhat obstruct chloride ingress. There was no big difference between cracks 0.2 mm and 0.4 mm wide or between locked and relaxed cracks.

SEM-EDS analyses of precipitations in the cracks showed that these mainly consisted of calcium hydroxide crystals of various size, and sometimes calcium carbonate crystals (calcite). In sea water needle-like sulphur containing crystals (e.g. ettringite) were frequent. For concrete that was exposed to cycles of sea water and drying magnesium hydroxide crystals (brucit) were found.

This report presents the results of part 1 of the project. In part 2 specimens will be exposed in sea water for about somewhat more than 2 years (28 months).

1. SELF-HEALING

Defects in concrete can heal more or less completely when it is exposed to high moisture level. Such self-healing, or autogenous healing, has been known for long time. An early review is given in Lauer&Slate (1956). According to these authors one of the first to report on the phenomenon was the well-known American concrete expert Duff Abrams (1913). Most of this early research, also the report by Lauer&Slate, dealt with the effect of autogenous healing on strength.

The effect of self-healing on *strength* depends on the following main factors:

- The initial crack width; smaller cracks seem to heal more completely in a given time than wide cracks.
- The extent of damage; specimens that are completely broken into separate pieces do not heal as much as specimens that still have a certain cohesiveness after damage.
- Pressure applied to the crack; cracks exposed to pressure heal more effectively in a given time than stress-free cracks. The extent of healing is bigger the higher the pressure.
- The moisture content; specimens stored in water heals more effectively than concrete that is exposed to high relative humidity. Dry concrete does not heal.
- The time in water after damage; the longer the storage time, the more effective the healing.

According to Dhir et al. (1973) complete restoration of *compressive strength* can occur in cement mortar specimens that are severely fractured (but not to complete failure) by high compressive load and then cured for some months at 95±3% RH. Also specimens that were fractured a second time, after the first healing, restored its compressive strength almost completely after some months curing.

In tests performed by Lauer&Slate (1956) cement paste specimens were completely fractured in *tension*. The one-axial tensile strength of un-fractured specimens was obtained for hydration times from 1 to 90 days. Specimens fractured at 1 day were healed in water or 95% RH and then fractured in direct tension once again after 7 days, 28 days and 90 days. Specimens fractured at 7 days were healed and re-fractured at 28 and 90 days. Specimens fractured at 28 days were healed and re-fractured at 90 days. Some specimens were re-fractured two times. During healing the two pieces of each fractured specimen were held together by a rubber band. The results showed that a certain healing occurred, but that it was much smaller than what has been observed for compressive strength. The maximum healing, about 25%, was obtained for specimens fractured at 1 day and re-tested at 90 days. Healing performed at 95% RH gave much smaller effect; the maximum healing was only about 4%.

The fact that *through cracks* in structures exposed to one-sided water pressure can heal has been known for long time. A well-established repair technique is to dry the downstream face so that lime precipitates in the crack opening thereby stopping the water flow. Extensive experimental work on healing of cracks with regard to permeability has been performed by Edvardsen (1996, 1999). An example from her work is shown in Figure 1.1. It shows flow through specimens with one single crack parallel to water flow at the water pressure 0.025 MPa (2.5 m hydraulic head). Complete healing is obtained after about 200 hours for the crack width 0.10 mm. Also cracks with 0.20 and 0.30 mm width heal almost completely within about 30 days.

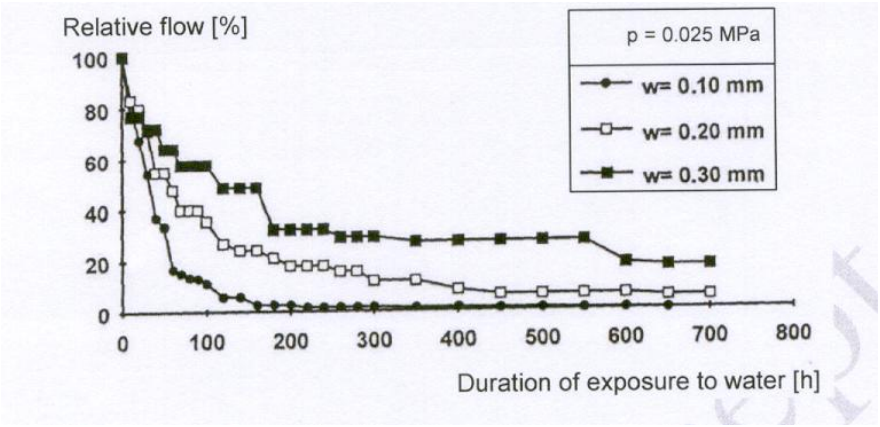

Figure 1.1: Influence of crack width and time on water flow under pressure; Edvardsen (1996).

Reports on the effect of healing of cracks with regard to chloride diffusion are scarce. Nordström (2005) exposed pre-cracked steel fibre reinforced concrete to salt spray from a Swedish highway. The exposure time was 5 years (5 winters) and the crack width was 0.1, 0.5 and 1 mm. Some results from measurements of the total chloride content on depths 2 mm to 4 mm from the crack wall, on different depths from the crack mouth, are shown in Figure 1.2. There is no clear certain tendency of reduced chloride content with increased depth in the crack. The chloride content on 45 mm depth varies between about 0.05 and 0.15 % of the cement weight. This can be compared with the chloride content on the same depth in un-cracked concrete, which is less than 0.02 % of the cement weight. Thus, chloride penetration in the crack is considerably higher. It must be noted that the specimens were exposed to seasonal variations in chloride and moisture exposure. Therefore, chloride can diffuse both inwards and outwards within the crack.

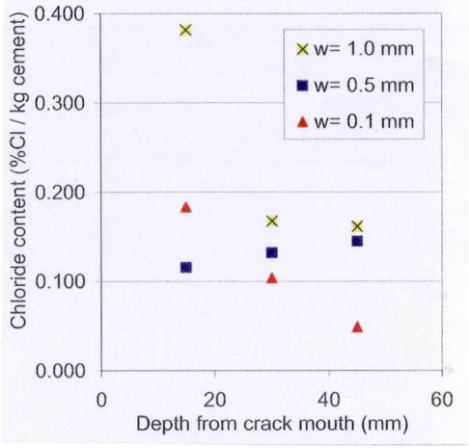

Figure 1.2: Chloride content in the crack wall after 5 winter exposure to salt spray from a Swedish highway. Effect of the crack width. Nordström (2005).

The following main mechanisms behind autogenous healing have been suggested:

- Continued hydration of the cement. The hydration products enter the crack and might eventually fill this completely. This effect ought to be most active when cracks appear early after production when there is still a large amount of un-reacted cement.
- Precipitation of $CaCO_3$ (calcite) by reaction of calcium ions in the pore solution with carbonate ions dissolved in the crack water.

The second mechanism is often claimed to be the major mechanism behind self-healing.

2. AIM

The aim of the project is:

- to investigate, visually and experimentally, the amount and type of precipitations in the crack after long-term exposure in different types of water (sea, brackish or pure).
- to investigate the effect of crack-healing on the ingress of chloride ions in cracks of different width when healing takes place in the presence of sea water or brackish water.

The ultimate aim is to investigate if the present rules as regards maximum tolerable crack widths in salt environment are reasonable, or if the crack width can be increased without increased risk of reinforcement corrosion.

3. THE CONCRETE

Only 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 *Anläggningscement* 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, since many years, used 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_3S	53%
C_2S	25%
C_3A	2%
C_4AF	13%
$(Na_2O)_{equiv}$ (soluble)	0,4%
Filler content	0%
Specific surface	320 m^2/kg
Strenth 1 day 28days	 10 MPa 54 MPa

Table 3.2: Mix characterisics

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, covered by plastic foil
- 2-14 days: Stored in lime-saturated water
- Day 14: Crack "fabricated"; see chapter 5.
- Day 14: Placed in different baths; see chapter 8.
- Exposure in bath for 375 to 385 days

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 of the specimen used for inducing the pre-crack.

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

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 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.

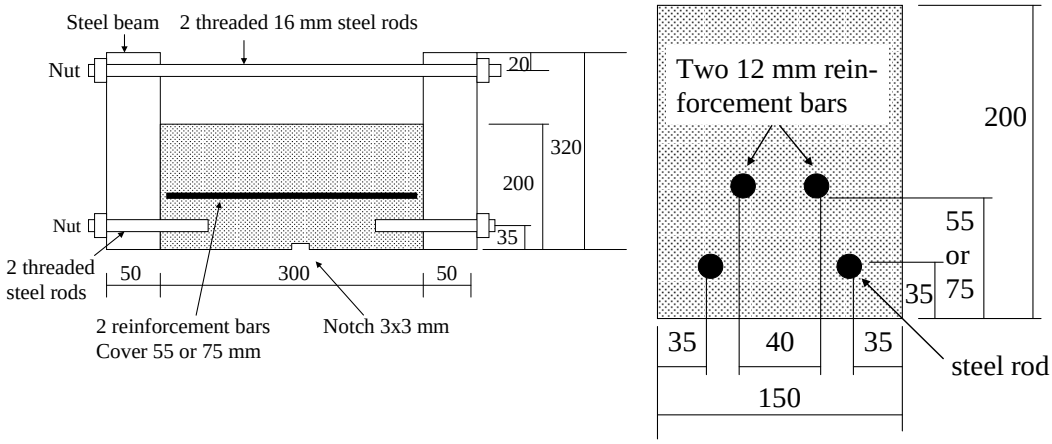

Figure 4.1: Specimen seen from the side and cross-section.

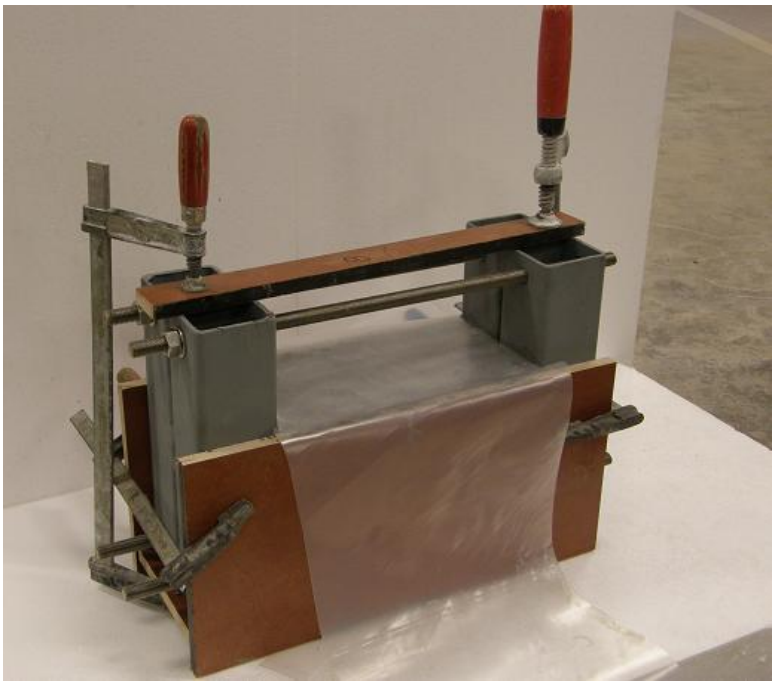

Figure 4.2: Specimen directly after casting.

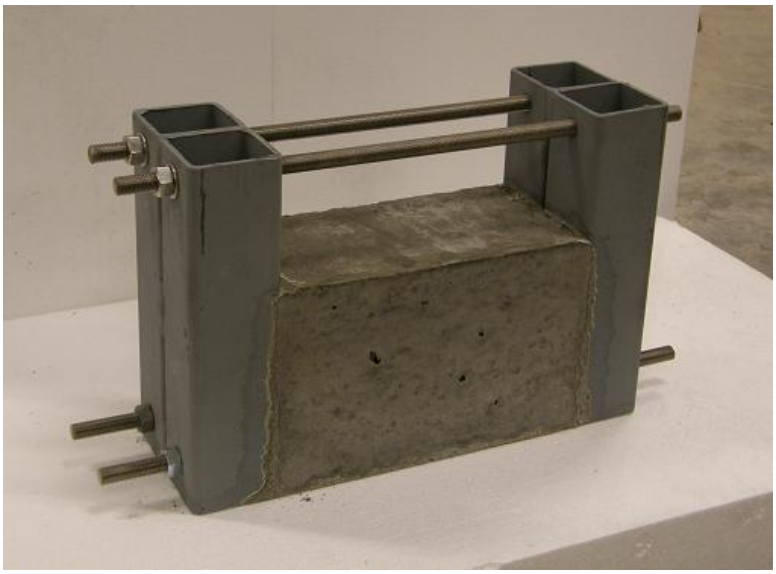

Figure 4.3: Specimen after de-moulding.

In total 34 specimens were cast. 18 of these were tested after 1 year exposure. The other 16 specimens will be tested after about 28 month exposure. In this report results for specimens stored for 1 year are given.

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 Linear Variable Displacement Transducers (LVDT) 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.

In one test series the cracks were allowed to relax. Therefore, the crack opening was not locked.

The test arrangement is shown in figure 5.2.

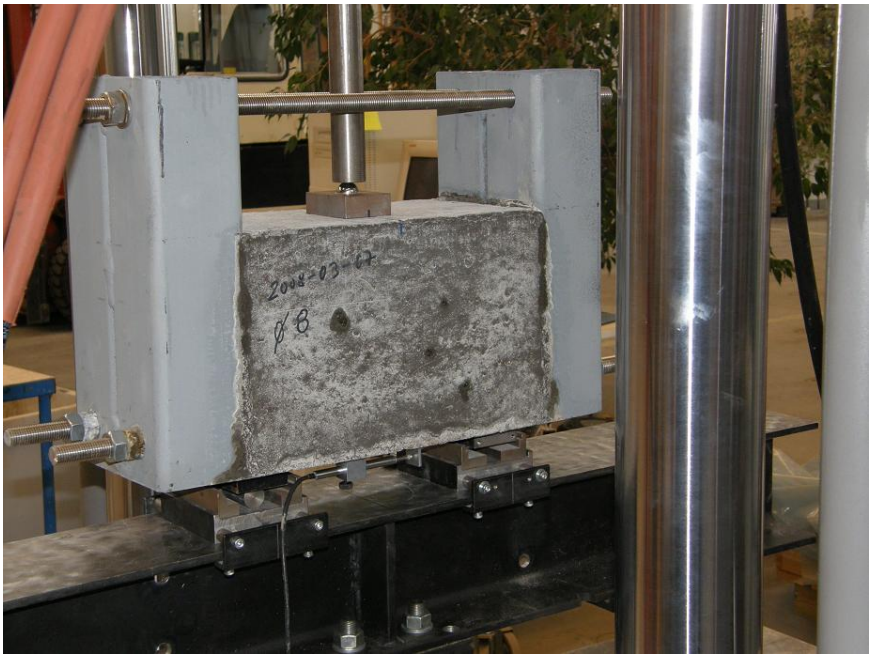

Figure 5.2: Test assembly for creating a crack in the specimen.

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 H75-4-1-1 left side).
Right: Crack width 0.2 mm (specimen H75-2-1-1 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 "silver-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.

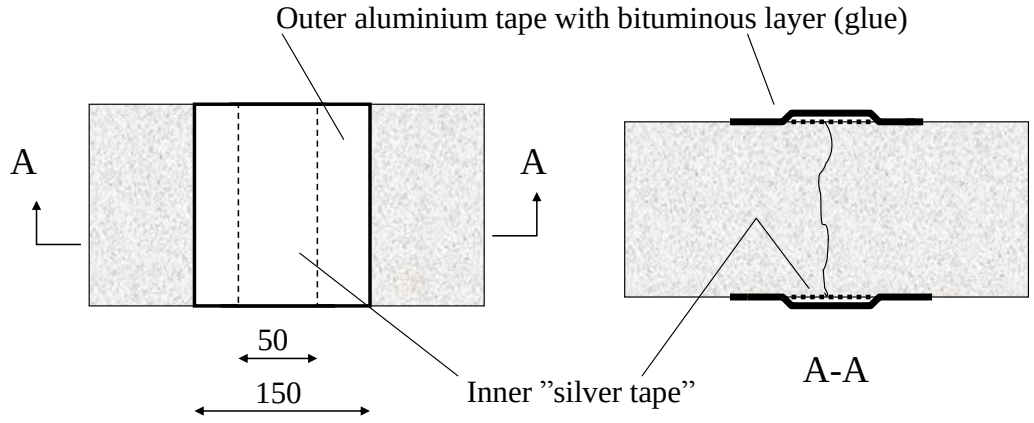

Figure 8.2: Sealing of the sides of the crack.

In one test series (Series 5) also the crack mouth was sealed in the same manner. Thus, water or salt could not enter the crack from outside, neither from the bottom nor, from the sides.

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.
  14 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. 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 one year. 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 25 cycles.
- Type 3: One-sided capillary suction. The specimens were turned upside down and the un-cracked upper surface immersed some millimetres in water. Drying occurred from the bottom "crack side". The specimens were stored in this way during one year. A basin with specimens is shown in figure 10.2. This type of exposure will go on for 2 years. Therefore, no results will be published in the present report.

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

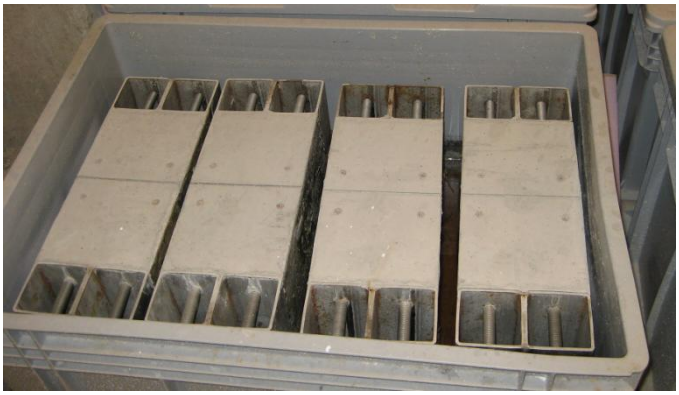

Figure 10.2: Water exposure type 3: Capillary suction from the un-cracked top side.

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 and 2
- Non-relaxed crack
- Open crack mouth

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

8 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	S155-4-1-1-Ö
	75	S175-4-1-1-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	S155-4-1-1-R
	75	S175-4-1-1-R

2 specimens

Test series 4: Relaxed crack
Variables:

- Sea water from the Swedish west-coast
- Crack width: 55 mm
- Exposure type: 1 and 2

Crack width (mm)	Concrete cover (mm)	Exposure	
		Type 1; immersed	Type 2; cyclic
0.4	55	H55-4R-1-1	H55-4R-2-1

2 specimens

Test series 5: Sealed crack opening
Variables:

- Crack width: 0.2 and 0.4 mm
- Concrete cover: 75 mm
- Exposure type: 1 and 2

Crack width (mm)	Concrete cover (mm)	Exposure	
		Type 1; immersed	Type 2; cyclic
0.2	75	S275-2-1-1	S2-75-2-2-1
0.4	75	S275-4-1-1	S2-75-4-2-1

4 specimens

12. PHOTOGRAPHS OF CRACKS AFTER 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 before exposure in figure 7.1. There is a clear indication of a certain healing, particularly of the thinner crack.

Figure 12.1: Photographs of cracks after exposure. The same specimens as in figure 7.1.
Left: Crack width 0.4 mm (specimen H75-4-1-1 left side).
Right: Crack width 0.2 mm (specimen H75-2-1-1 left side).

More photos of cracks in the lower part (1 to 3 or 4 cm from the crack tip) for all 18 specimens are given in APPENDIX 1. In each picture, comparison is made of the crack before and after exposure. For each specimen both sides of the crack are shown.

Magnifications of photos of the lowest part of the crack after 1 year exposure are shown in figure 12.2-12.11 for 10 specimens. Only one side of the specimens are shown. The other side is similar to the side shown.

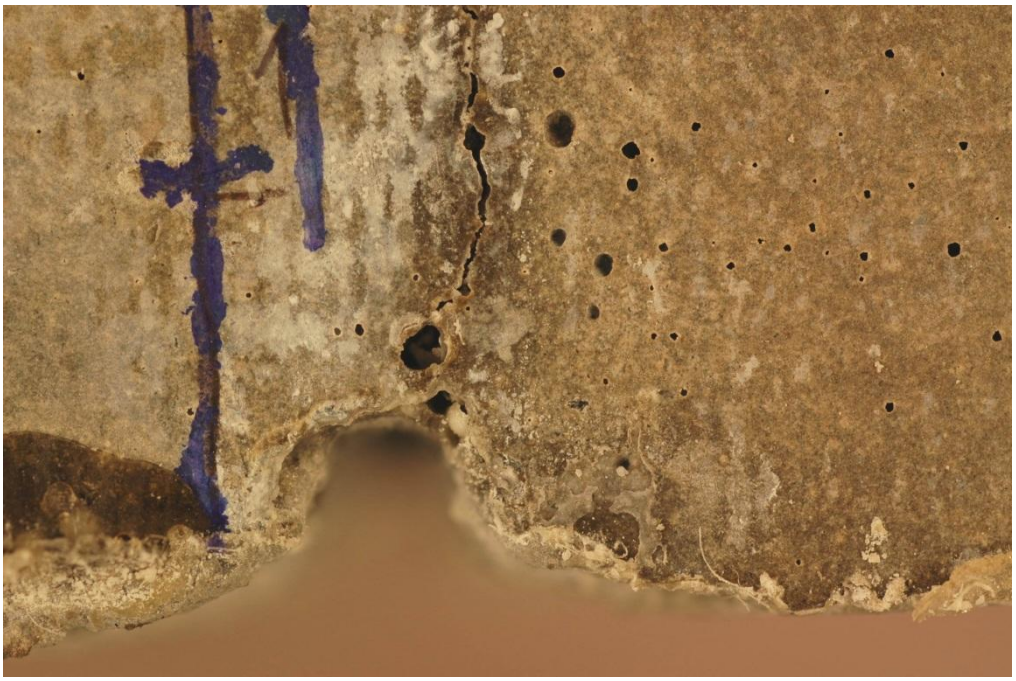

Figure 12.2: 0.2 mm crack after 1 year permanent immersion in sea water. Test series 1, specimen H75-2-1-1.

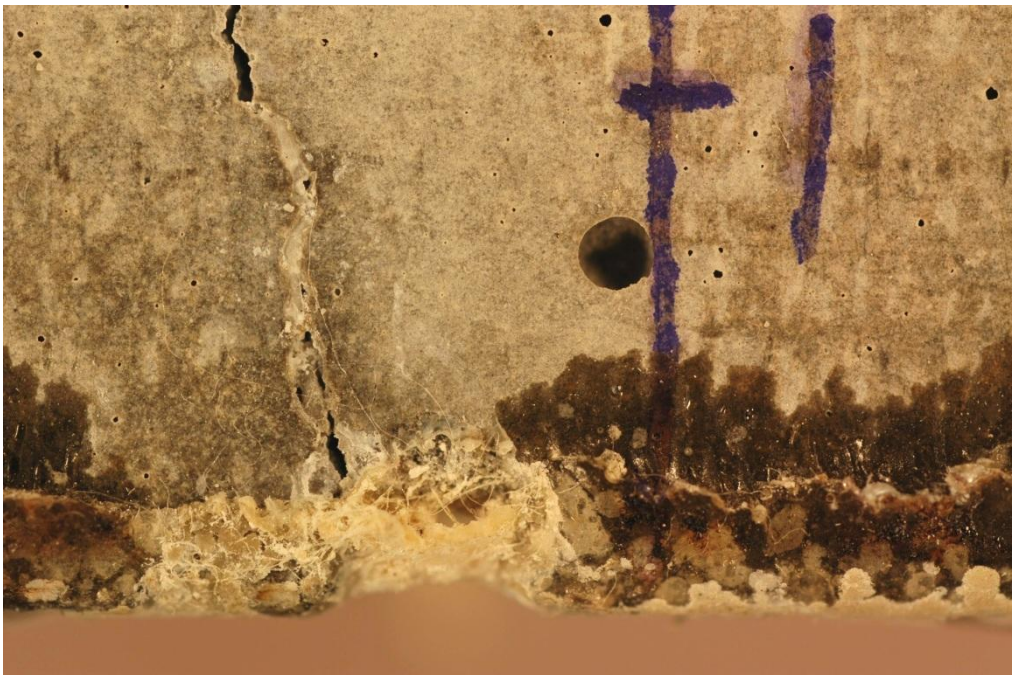

Figure 12.3: 0.4 mm crack after 1 year permanent immersion in sea water. Test series 1, specimen H75-4-1-1.

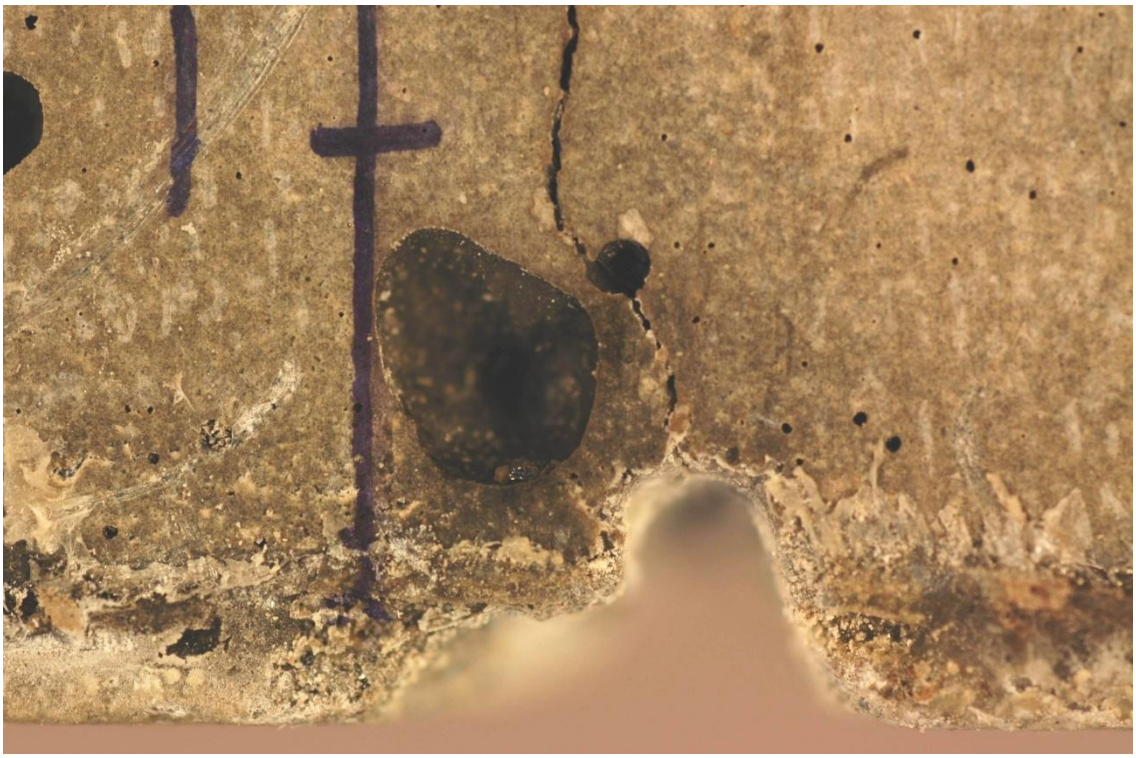

Figure 12.4: 0.2 mm crack after 1 year cyclic immersion in sea water and drying. Test series 1, specimen H75-2-2-1.

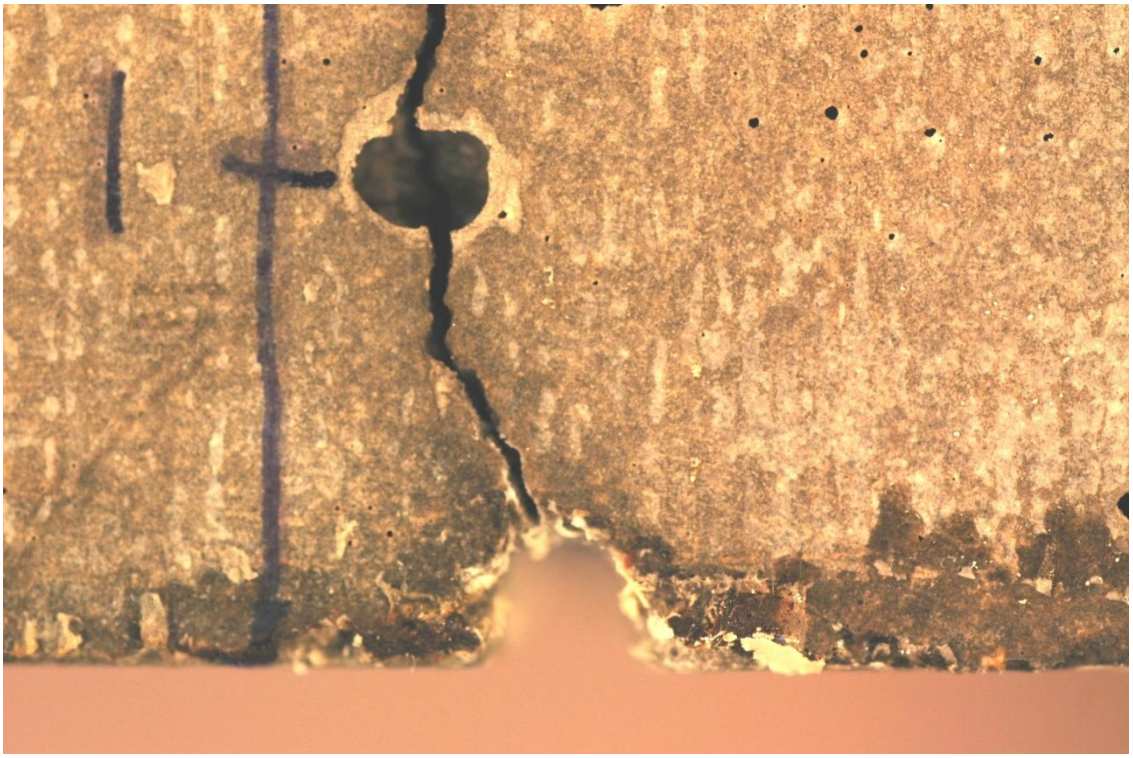

Figure 12.5: 0.4 mm crack after 1 year cyclic immersion in sea water and drying. Test series 1, specimen H75-4-2-1.

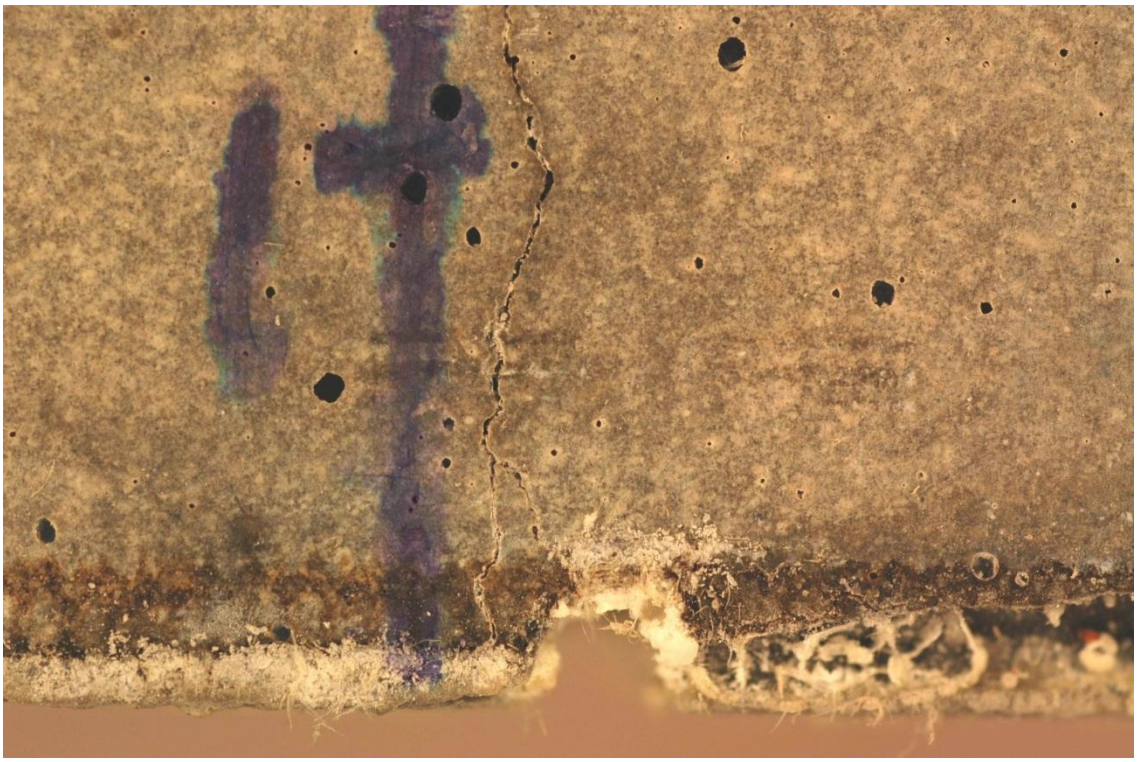

Figure 12.6: 0.4 mm relaxed crack after 1 year permanent immersion in sea water. Test series 1, specimen H55-4R-1-1.

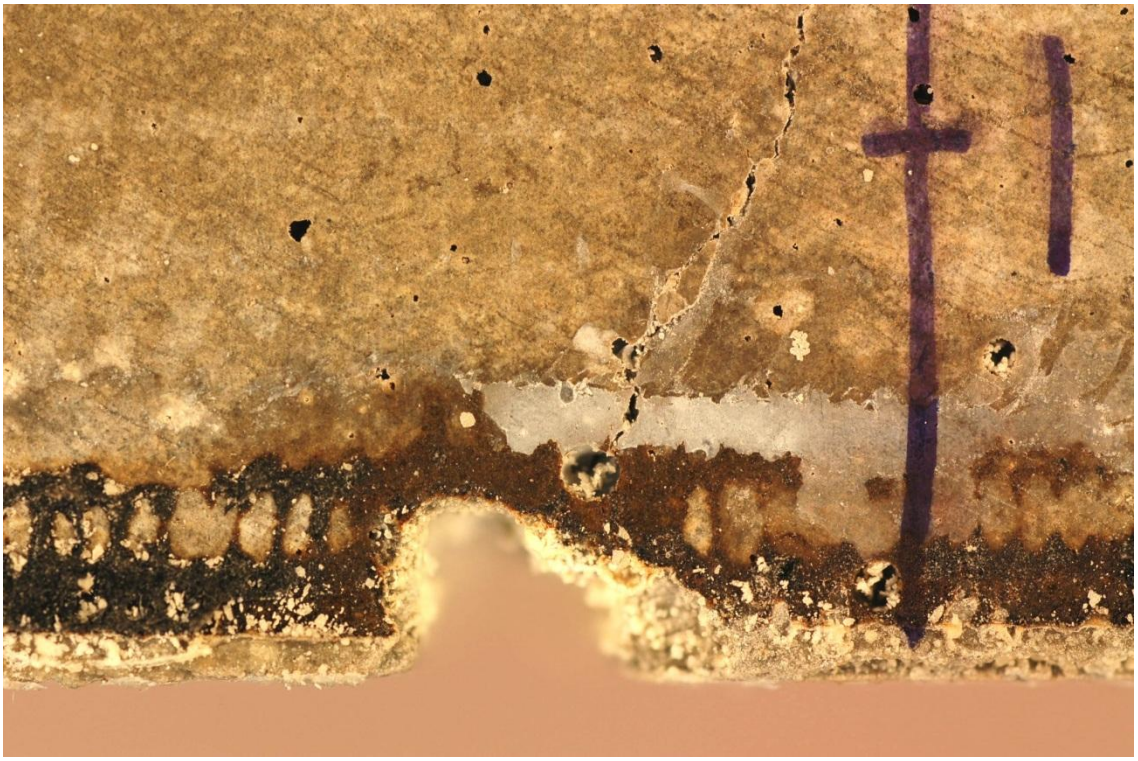

Figure 12.7: 0.4 mm relaxed crack after 1 year cyclic immersion in sea water and drying. Test series 1, specimen H55-4R-2-1.

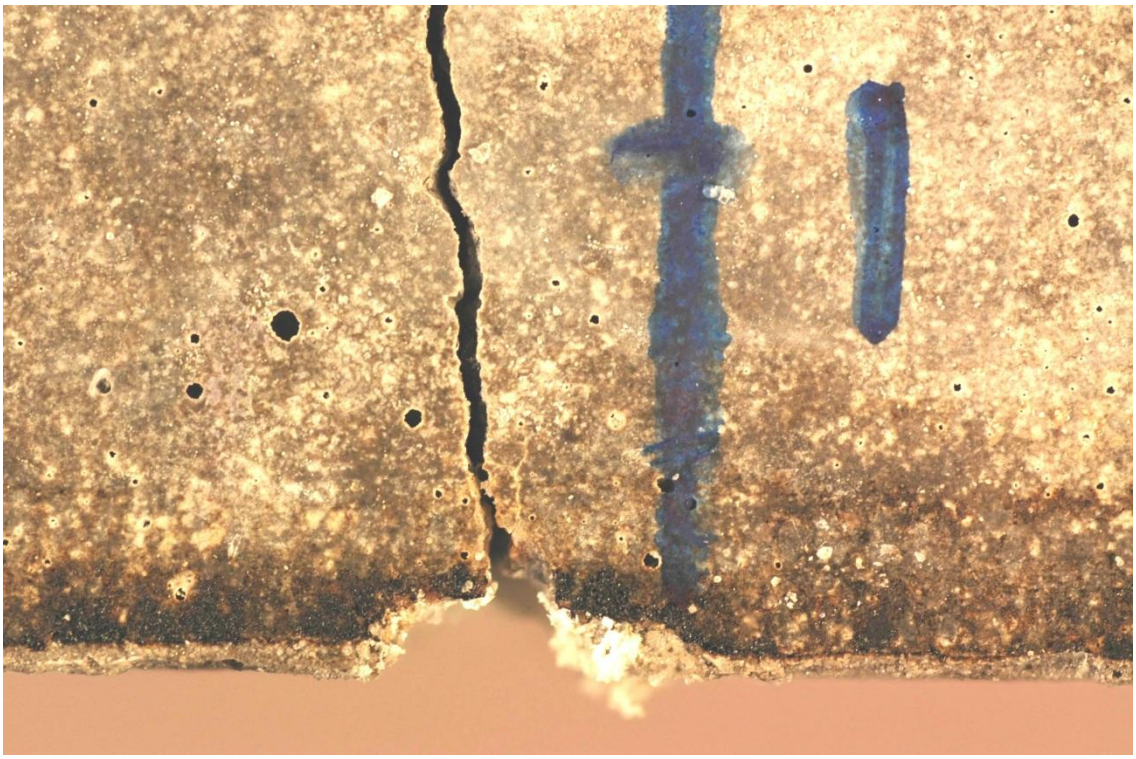

Figure 12.8: 0.4 mm crack after 1 year permanent immersion in pure water.
Test series 3, specimen S175-4-1-1-R.

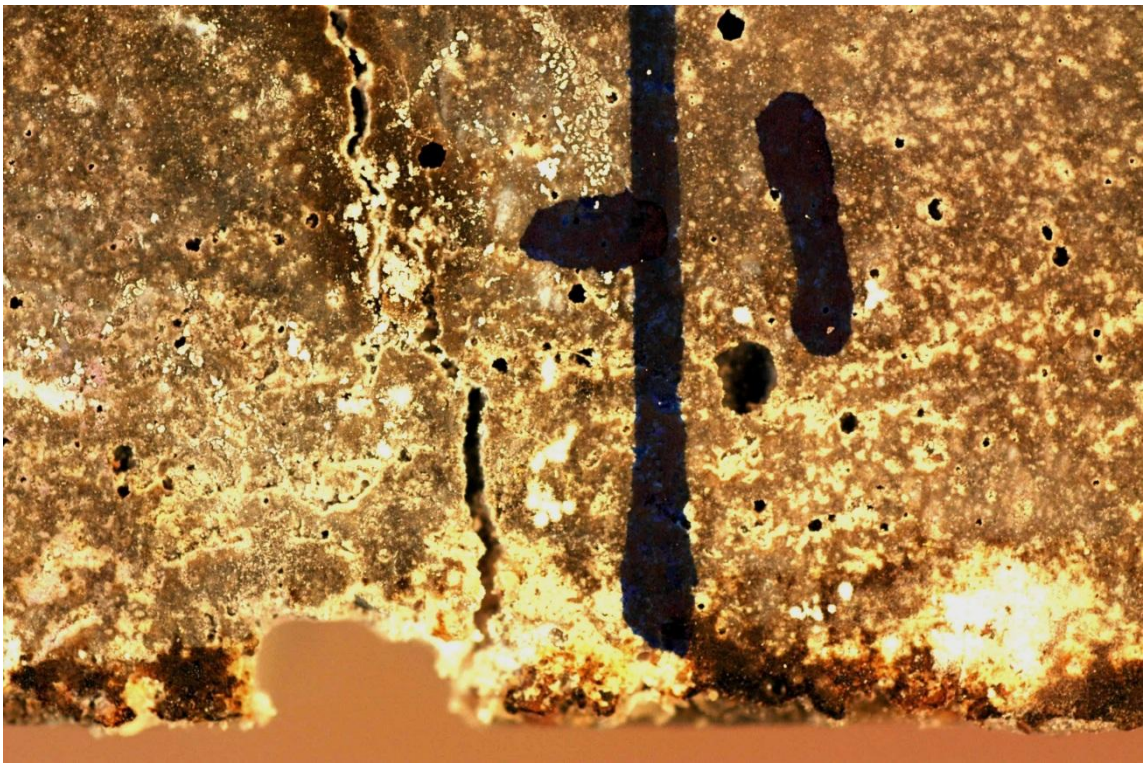

Figure 12.9: 0.4 mm crack after 1 year permanent immersion in brackish water.
Test series 2, specimen S175-4-1-1-Ö.

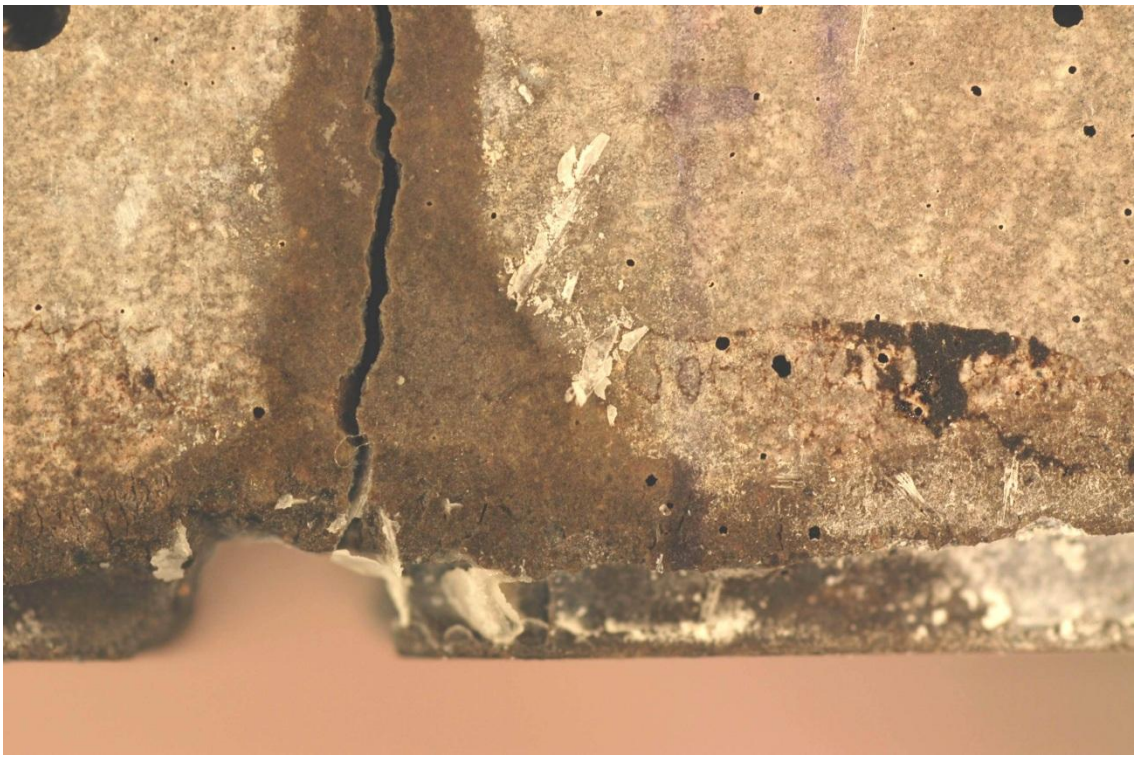

Figure 12.10: 0.4 mm sealed crack after 1 year permanent immersion in sea water. Test series 5, specimen S275-4-1-1.

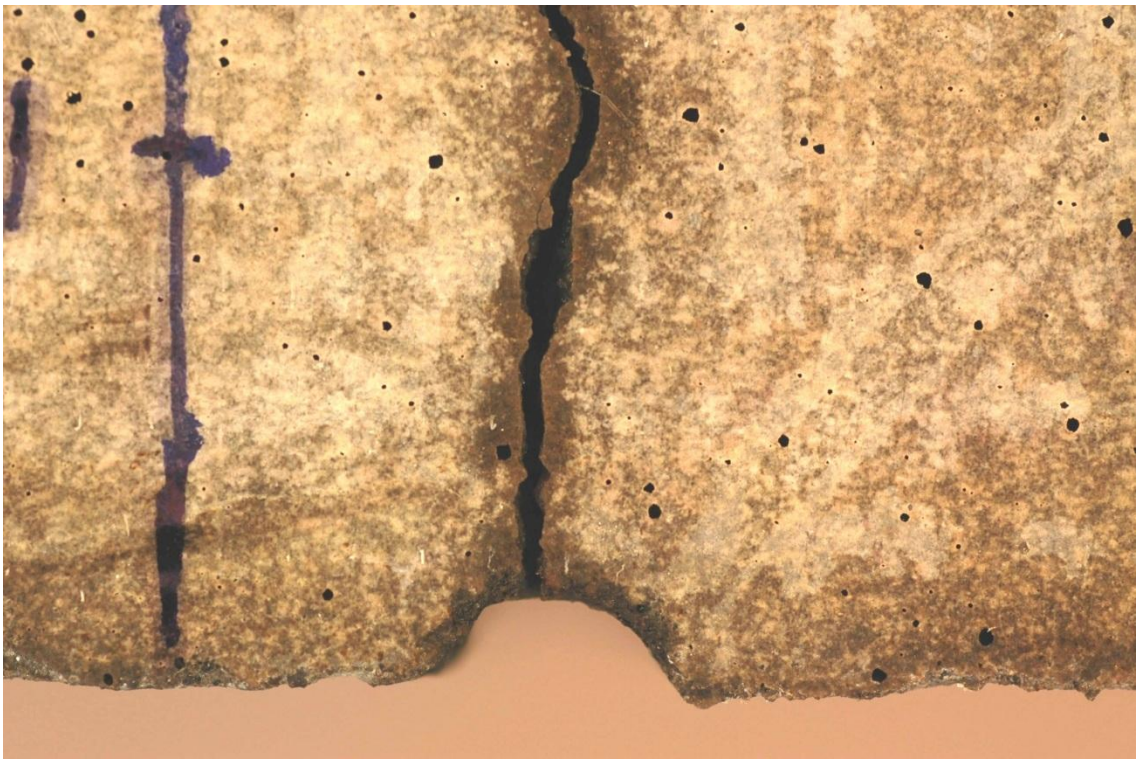

Figure 12.11: 0.4 mm sealed crack after 1 year cyclic immersion in sea water and drying. Test series 5, specimen S275-4-2-1.

The following observations are made:

- Figure 12.2-12.3: At *permanent immersion* in sea water there are clear visual indications of a certain healing at the bottom of the crack, also for the crack width 0.4 mm.
- Figure 12.4-12.5: At *cyclic immersion and drying* the healing seems to be smaller than at permanent immersion, especially for the crack width 0.4 mm.
- Figure 12.6-12.7: There seems to be no bigger healing for *relaxed cracks* compared to the non-relaxed 0.4 mm cracks, cf. figure 12.2-12.3.
- Figure 12.8-12.9: There are no signs of self-healing of 0.4 mm cracks at storage in *tap water* but small signs of healing at storage in *brackish water*.
- Figure 12.10-12.11: When the crack mouth is *sealed* there are no visual signs of self-healing.

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

- Figure A2.1-A2.2: *Permanent immersion*: Visually, certain healing of 0.2 mm crack. No healing of 0.4 mm crack.
- Figure A2.3-A2.4: *Cyclic immersion and drying*: No healing of cracks visible.
- Figure A2.5-A2.6: *Relaxed 0.4 mm cracks*: Certain healing observable both for permanent immersion and cyclic immersion and drying.
- Figure A2.7-A2.8: *Brackish water and tap water*: No signs of healing of 0.4 mm cracks in tap water but slight indication of healing in brackish water.
- Figure A2.9-A2.10: *Sealed crack mouth*: No signs of healing at permanent immersion but indications of certain healing at cyclic immersion and drying.

13. DRILLING OF CORES AFTER EXPOSURE

After terminated exposure a 10 cm core was drilled centrically 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 13.1. An example of a drilled-out core is shown in figure 13.2.

Figure 13.1: Example of a specimen after the core has been drilled out.

Figure 13.2: Example: core drilled out from specimen S1-75-4-1-1-R (75 mm cover, crack width 0.4 mm, permanently exposed to pure water).
Photo: Kalinowski&Fjällberg (2010).

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

14. ANALYSIS OF MINERALS AND CHLORIDE CONCENTRATION IN CRACK WALLS

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

- Composition and morphology of minerals precipitated in the crack on three different depths from the crack mouth (5, 25 and 55 mm).
- Concentration of chloride ions in the outermost 5 mm of the crack wall on four 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 14.1.

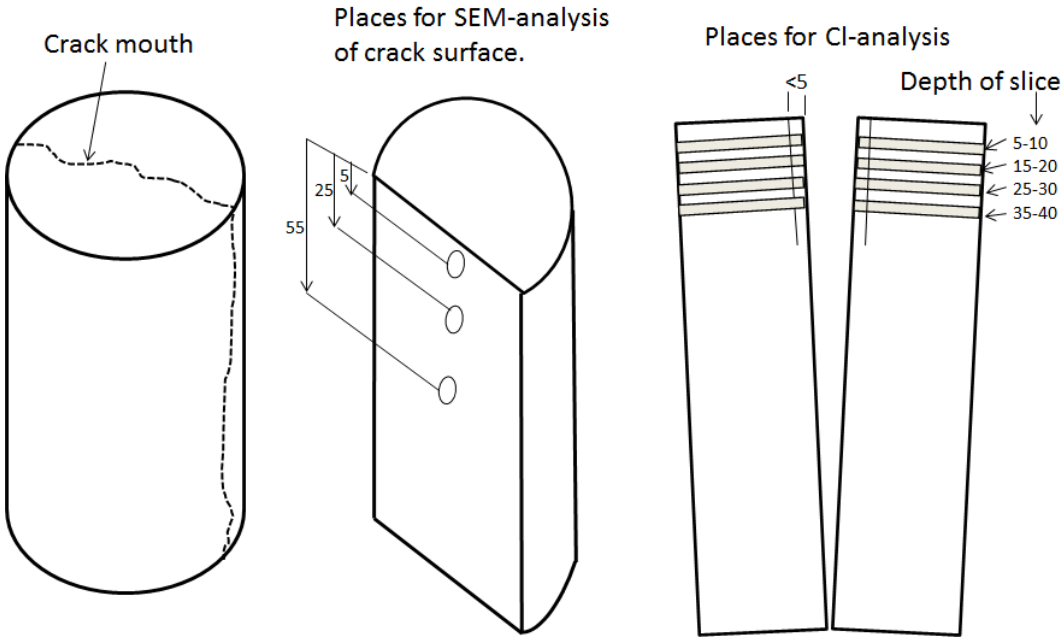

Figure 14.1: Core and places where samples were taken from the crack walls.

All test results have been published in a report by Kalinowski & Fjällberg (2010). Results from this report are presented below.

14.1 Mineral composition of precipitations in cracks

Each area in which mineral analysis was made had an area of at least 10 mm^2.

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.

SEM-photos of precipitations in the crack for specimens stored permanently in sea water are shown in Figure 14.2. SEM photos for specimens permanently stored in brackish water or tap water is shown in Figure 14.3 and 14.4. SEM photos for specimens cyclically exposed to sea water and drying in air are shown in figure 14.5.

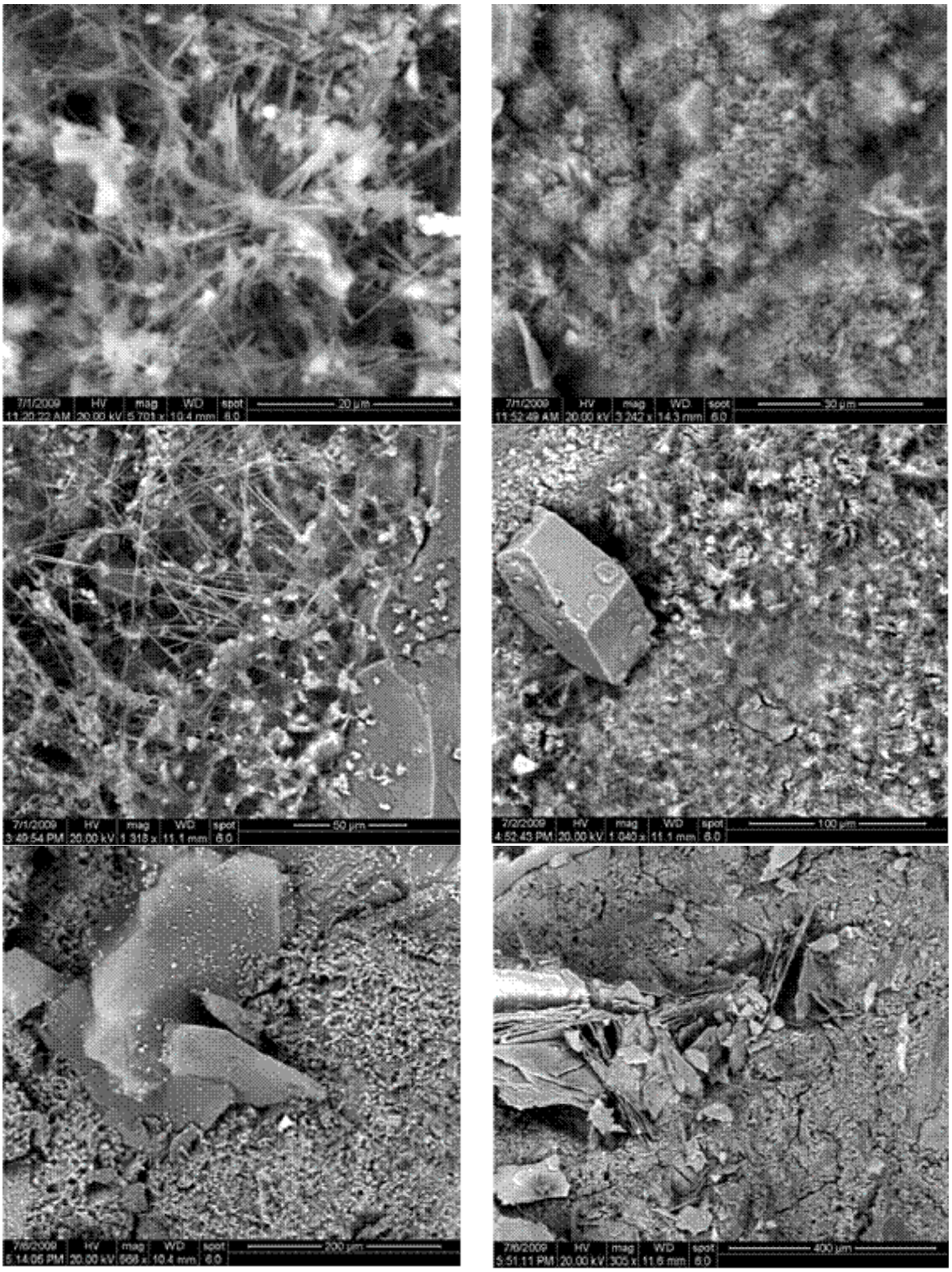

*Figure 14.2: SEM-photos of precipitations in cracks for specimens **exposed permanently in sea water**. Photos: Kalinowski & Fjällberg (2010).*
***Upper row:** Cover 55 mm. Crack 0.2 mm. Specimen H55-2-1-1.*
Left: Depth 5 mm. Right: Depth 55 mm.
***Middle row:** Cover 55 mm, Crack 0.4 mm.*
Left: Specimen H55-4-1-1.Depth 55 mm.
Right: Specimen H55-4R-1-1. Relaxed crack. Depth 5 mm.
***Lower row:** Cover 75 mm. Crack 0.2 mm. Specimen S275-2-1-1. Sealed crack*
Left: Depth 5 mm. Right: Depth 55 mm.

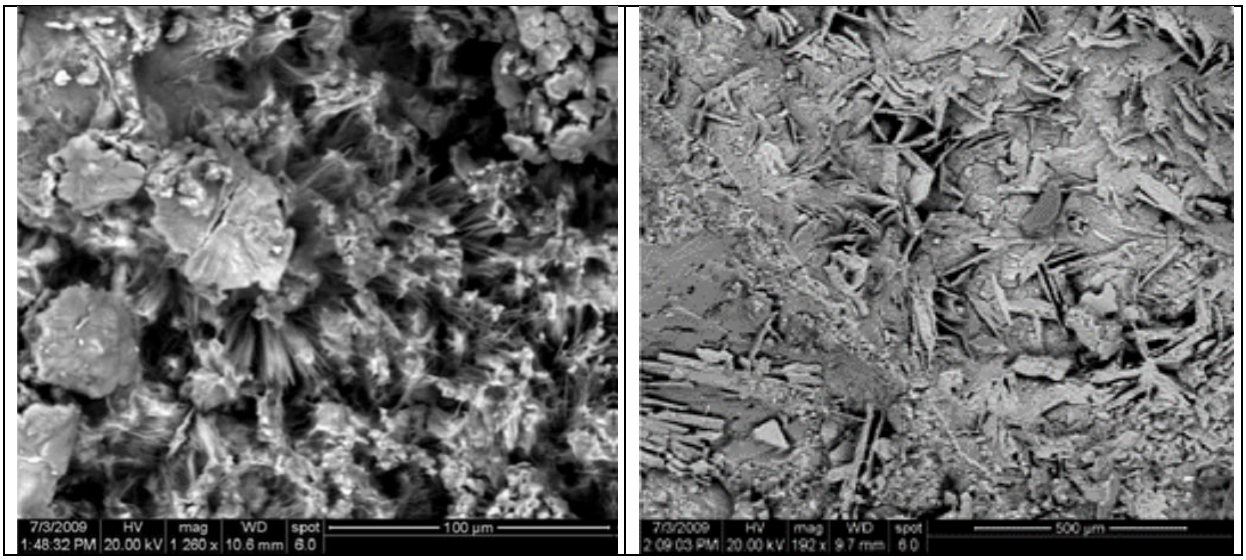

*Figure 14.3: SEM-photos of precipitations in cracks for specimens **exposed permanently in brackish water**. Photos: Kalinowski & Fjällberg (2010).*
Cover 55 mm. Crack width 0.4 mm. Specimen S155-4-1-1-Ö.
Left: Depth 5 mm. Right: Depth 55 mm.

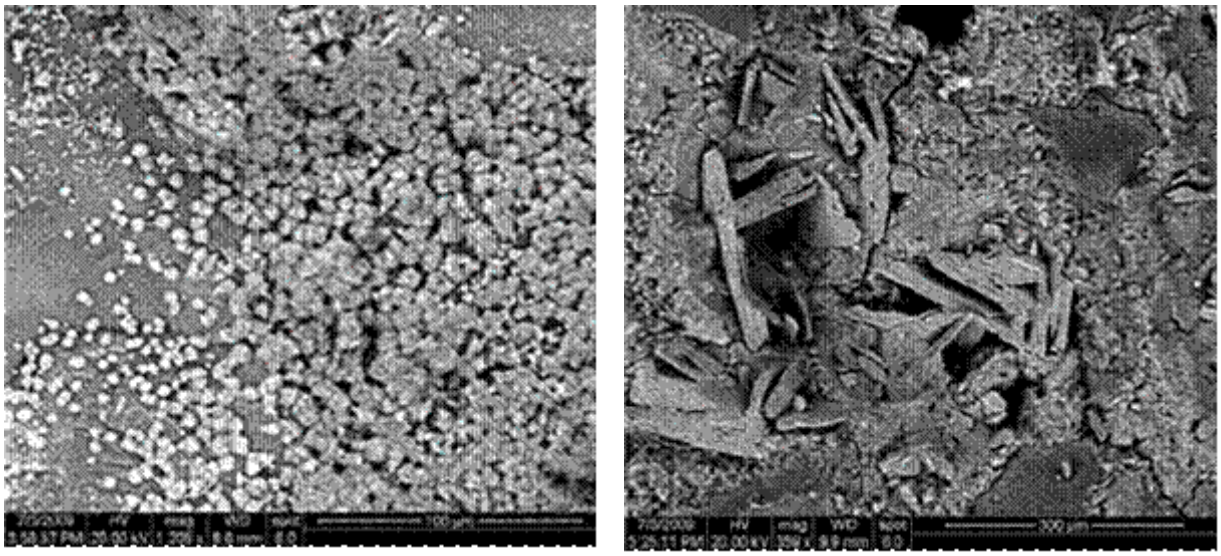

*Figure 14.4: SEM-photos of precipitations in cracks for specimens **exposed permanently in tap water**. Photos: Kalinowski & Fjällberg (2010).*
Cover 55 mm. Crack width 0.4 mm. Specimen S155-4-1-1-R.
Left: Depth 5 mm. Right: Depth 55 mm.

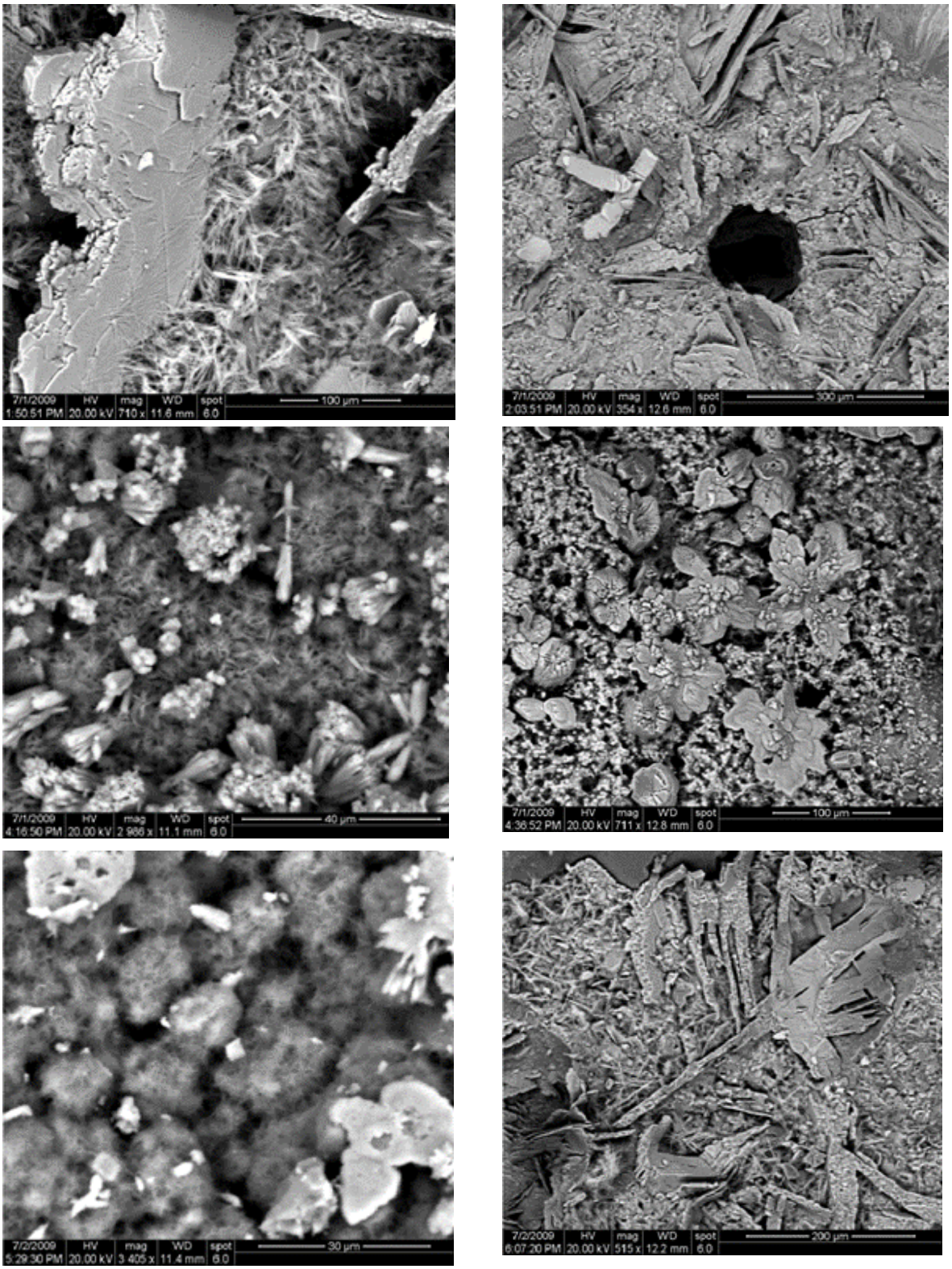

*Figure 14.5: SEM-photos of precipitations in cracks for specimens **exposed to cyclic immersion in sea water and drying**. Photos: Kalinowski & Fjällberg (2010).*
***Upper row:** Cover 55 mm. Crack 0.2 mm. Specimen H55-2-2-1.*
Left: Depth 25 mm. Right: Depth 55 mm.
***Middle row:** Cover 55 mm, Crack 0.4 mm. Specimen H55-4-2-1.*
Left: Depth 5 mm. Right: Depth 55 mm.
***Lower row:** Cover 55 mm. Crack 0.4 mm. Specimen H55-4R-2-1. Relaxed crack*
Left: Depth 5 mm. Right: Depth 55 mm.

Types and composition of different precipitated compounds in the cracks of 10 specimens are described in APPENDIX 3. The following compounds were frequently observed on all depths from 5 to 55 mm:

- Big plate-like $Ca(OH)_2$-crystals and smaller cubic $Ca(OH)_2$-crystals.
- Needle-like crystals composed of the elements aluminium, silicon, sulphur and calcium; probably ettringite or other sulphur-containing compound.
- Brucit ($Mg(OH)_2$). This was mainly observed in specimens exposed to cyclic exposure (Table A3.2).

In the report Kalinowski&Fjällberg (2010) the following statements are made:

- "Precipitations on crack walls were observed in all specimens."
- "The precipitations consist of very fine-graded and thin coatings on the crack walls. Moreover, bigger crystals or crystal aggregates occur."
- "Crystals of calcium hydroxide and calcium carbonate are big enough to bridge the two crack surfaces."
- "The amount of crystals varies between different depths in the crack and is different in different specimens."
- "The degree of crack-filling can be described as low in all specimens. Our judgement is that the precipitations have not implied a healing of the cracks to an extent that it can hinder penetration of moisture and chloride, i.e. (the healing) has no significance with regard to durability".
  Comment: Direct measurements of chloride penetration -see below- partly contradicts this last conclusion.

14.2 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 14.1. The outer 5 mm from each slice was broken loose and used for chloride analysis. 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.

The results are shown in figure 14.6-14.10. The following conclusions can be drawn:

- For all specimens *stored in salt water (sea or brackish)* the salt concentration decreases with increasing distance from the crack tip. Since the crack widths are quite big, this shows that the precipitation in cracks obstructs the inflow of chloride.
- Specimens *permanently stored in sea* water reaches a total chloride content of about 2% on the depth 7.5 mm and about 0.5% on 37.5 mm depth. The chloride content is more or less independent on the thickness of the cover (figure 14.6).
- For specimens *permanently stored in sea water* the crack width 0.4 mm seems to give somewhat lower chloride content in the outer part of the crack than 0.2 mm. On bigger depth this difference vanishes (figure 14.6).
- At *cyclic immersion and drying in sea water* the chloride content on bigger depth reaches about the same level as permanent immersion; i.e. about 0.5% (figure 14.7). However, the cover seems to have some effect for the thinner crack; 55 mm cover gives much lower ingress of chloride than 75 mm cover when the crack width is only 0.2 mm.
- The *relaxed crack* does not reduce ingress of chloride (figure 14.8).
- Immersion in *brackish water* reduces the chloride content by about 50%. About 0.9% is reached at the outer part of the crack and about 0.3% at bigger depth (figure 14.9).
- Specimens stored in *pure water* have very low chloride content on all depths which shows that the sealing of crack sides has worked (figure 14.10).
- Specimens with *sealed crack mouth* have low chloride content on all depths (figure 14.10). The chloride level is however somewhat higher than for specimens stored in pure water, especially close to the crack tip, which indicates that the seal of the crack mouth has not been perfect.

Theoretically, the chloride profiles can be used for estimation of the chloride diffusion coefficient in cracks using Fick´s law:

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

where
c_x is the chloride content on depth x (m)
c_s is the chloride content at the surface (crack mouth)
x is the depth (m)
δ is the (effective) chloride diffusion coefficient (m^2/s)
t is the exposure time (s)

The equation implies that there is no time delay caused by penetration into the 5 mm thick 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, they can be obtained by applying the equation to the measured chloride distribution curves, provided chloride binding is linear (the relation between free and bound chloride is constant). The actual curves give different values of surface concentration depending on which points of the curves 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. This means that the diffusion coefficient will vary depending on which point on the curves is used. The result of the application of Fick´s law gives the diffusivities listed in table 14.1 and 14.2.

Table 14.1: 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 $\cdot 10^{-12}$ (m^2/s)
H55-2-1-1 Fig 14.6	0.4	55	2.5	7.5 17.5 27.5 37.5	6.0 9.0 11.4 16.4
			3.0	7.5 17.5 27.5 37.5	3.0 6.2 9.4 13.8
			Mean		9.4
H55-4-1-1 Fig 14.6	0.2	55	2.5	7.5 17.5 27.5 37.5	14.6 13.4 11.3 11.4
			3.0	7.5 17.5 27.5 37.5	5.0 8.7 8.8 10.1
					10.4
H55-4R-1-1 Relaxed crack Fig 14.8	0.4	55	2.5 (unrealistic low value; see fig 27)		
			3.0	7.5 17.5 27.5 37.5	11.2 10.8 10.7 13.7
					11.6
			3.5	7.5 17.5 27.5 37.5	5.0 8.0 9.4 11.6
					8.5

Table14.2: 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)
S175-4-1-1 Fig 14.9	0.4	55	1.5	7.5 17.5 27.5 37.5	3.4 13.5 15.4 15.8
			2.0	7.5 17.5 27.5 37.5	1.6 7.4 9.4 12.4
			Mean		9.8
S175-4-1-1 Fig 14.9	0.4	75	1.5	7.5 17.5 27.5 37.5	2.2 4.8 8.3 12.4
			2.0	7.5 17.5 27.5 37.5	1.2 3.4 6.6 9.6
					6.0

The value of the diffusion coefficient depends on the assumption concerning the surface concentration and on the choice of location on the chloride concentration curve. The range is from about $6 \cdot 10^{-12}$ to $10 \cdot 10^{-12}$ m^2/s with the mean value $9 \cdot 10^{-12}$ m^2/s.

The chloride diffusion coefficient for un-cracked concrete of the actual quality can be expected to be of the order $1 \cdot 10^{-12}$ à $5 \cdot 12^{-12}$ m^2/s. The diffusion coefficient of the healed crack is higher but still low enough to indicate that even a rather coarse crack (0.4 mm) is able to form a certain barrier to chloride penetration. If there was no barrier the chloride concentration ought to be almost the same on all depths since in such a case one should expect the same chloride concentration in the “crack water” on all depths.

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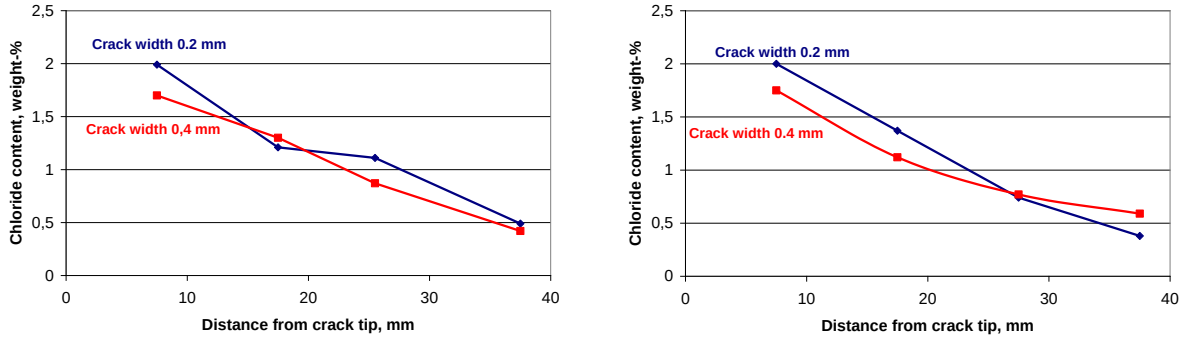

Figure 14.6: Chloride content in crack walls. Permanently immersed in sea water. Effect of crack width. Left figure: Cover 55 mm. Right figure: Cover 75 mm.

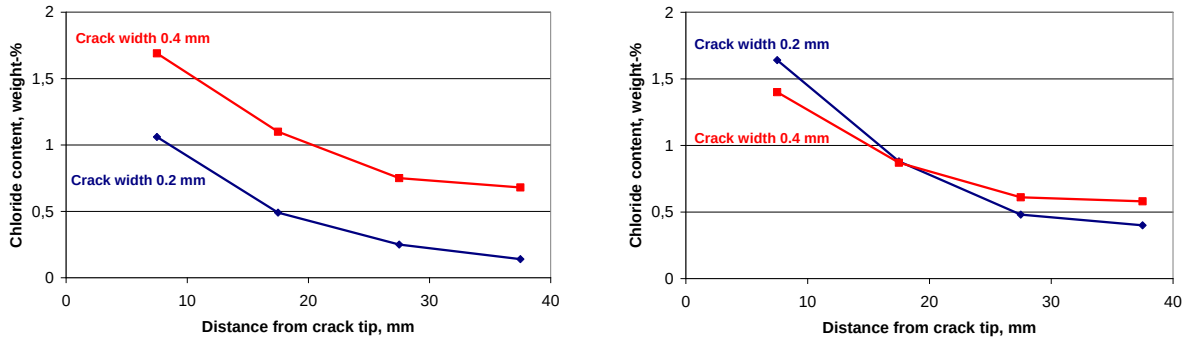

Figure 14.7: Chloride content in crack walls. Cyclic immersion and drying in sea water. Effect of crack width. Left figure: Cover 55 mm. Right figure: Cover 75 mm.

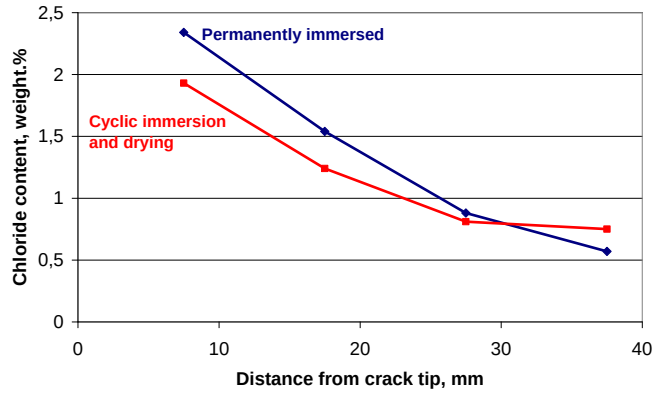

Figure 14.8: Chloride content in crack walls. Relaxed crack. Effect of type of exposure. Cover 55 mm. Crack width 0.4 mm.

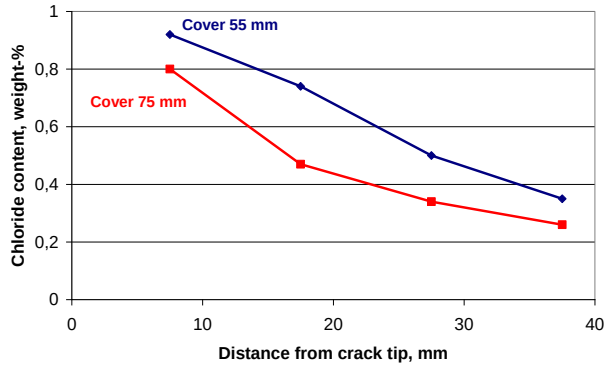

Figure 14.9: Chloride content in crack walls. Permanently immersed in brackish water. Effect of cover. Crack width 0.4 mm.

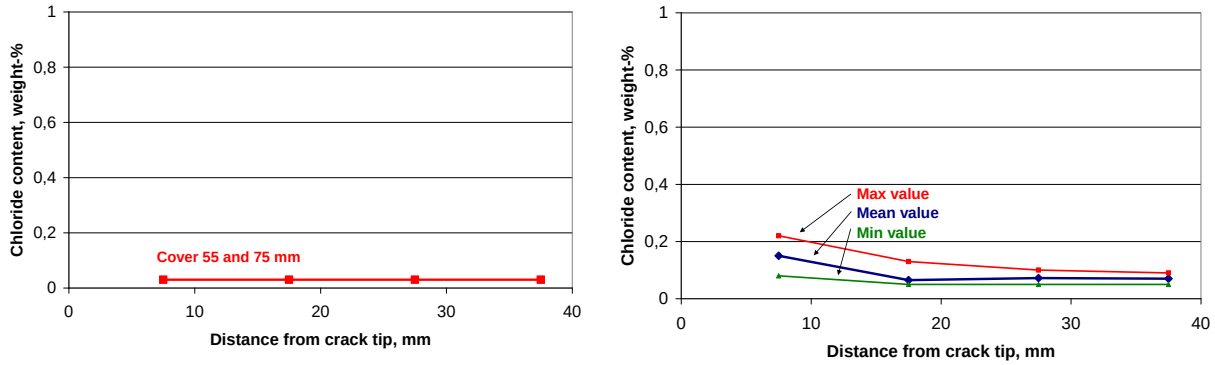

Figure 14.10: Chloride content in crack walls.
Left figure: Permanent exposure in tap water (2 specimens).
Right figure: Sealed crack opening. 4 specimens with crack width 0.2 and 0.4 mm. 2 specimens permanently immersed. 2 specimens exposed to cyclic immersion and drying.

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APPENDIX 1

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

A: Specimens exposed to sea water from the Swedish west coast

A.1: Specimens permanently immersed in sea water

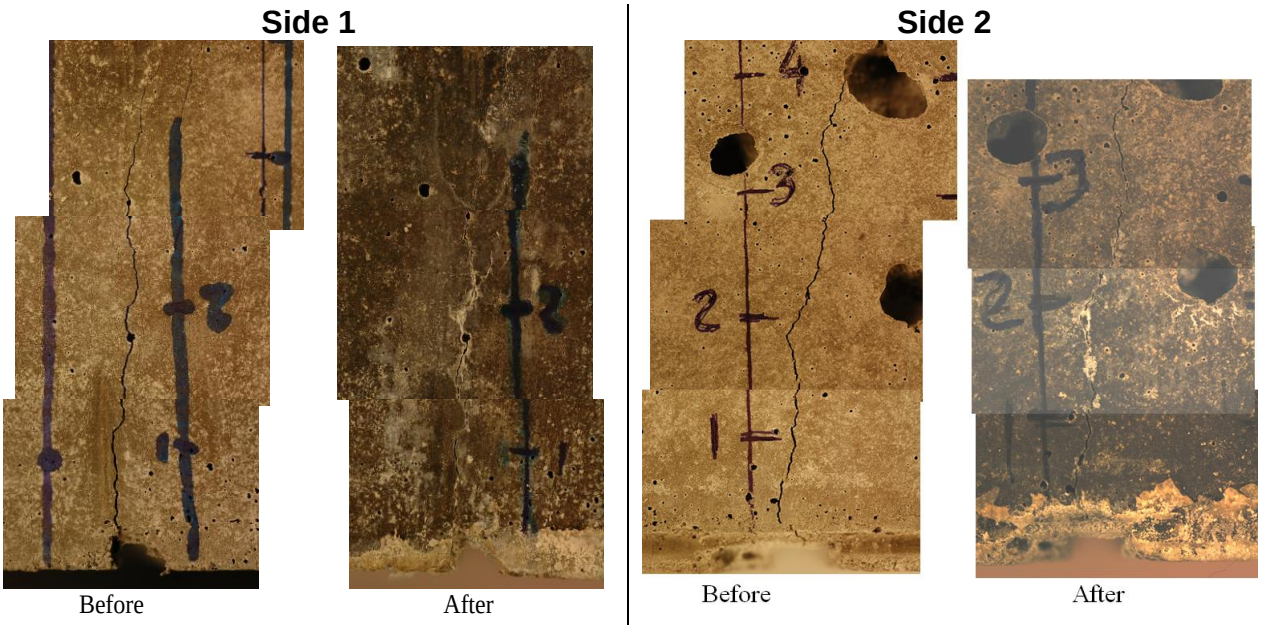

Figure A1.1: Permanently in sea water.
Crack width 0.2 mm. Cover 55 mm. Specimen H55-2-1-1

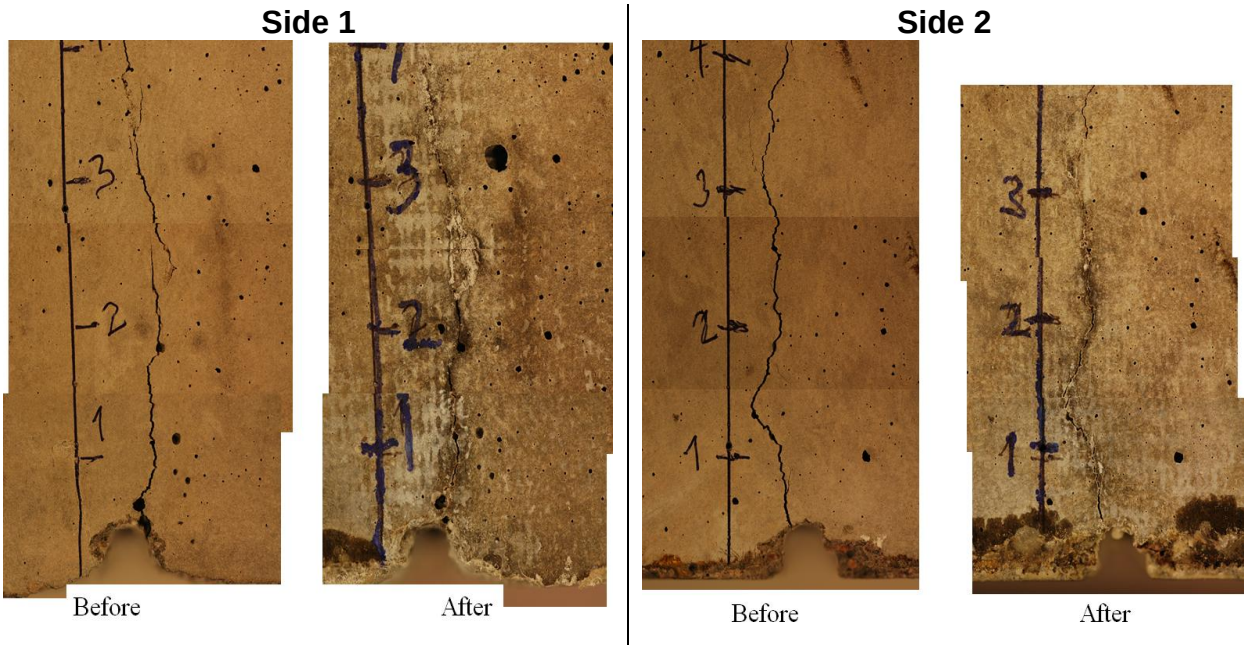

Figure A1.2: Permanently in sea water.
Crack width 0.2 mm. Cover 75 mm. Specimen H75-2-1-1

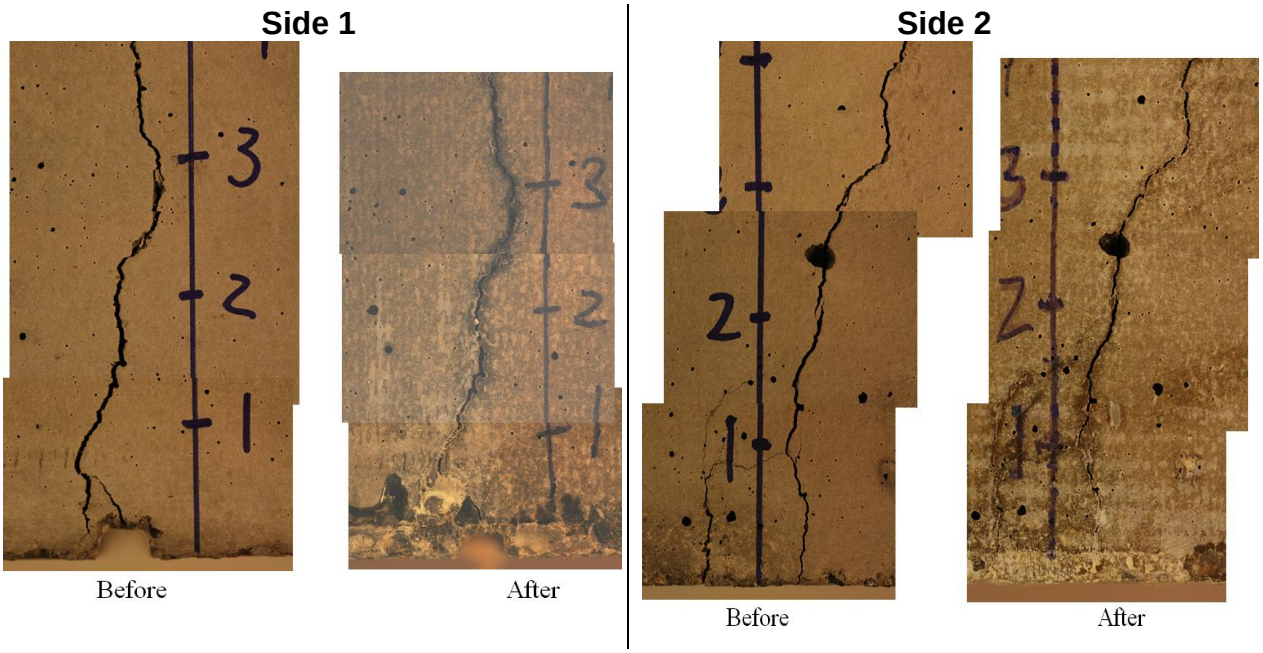

Figure A1.3: Permanently in sea water.
Crack width 0.4 mm. Cover 55 mm. Specimen H55-4-1-1

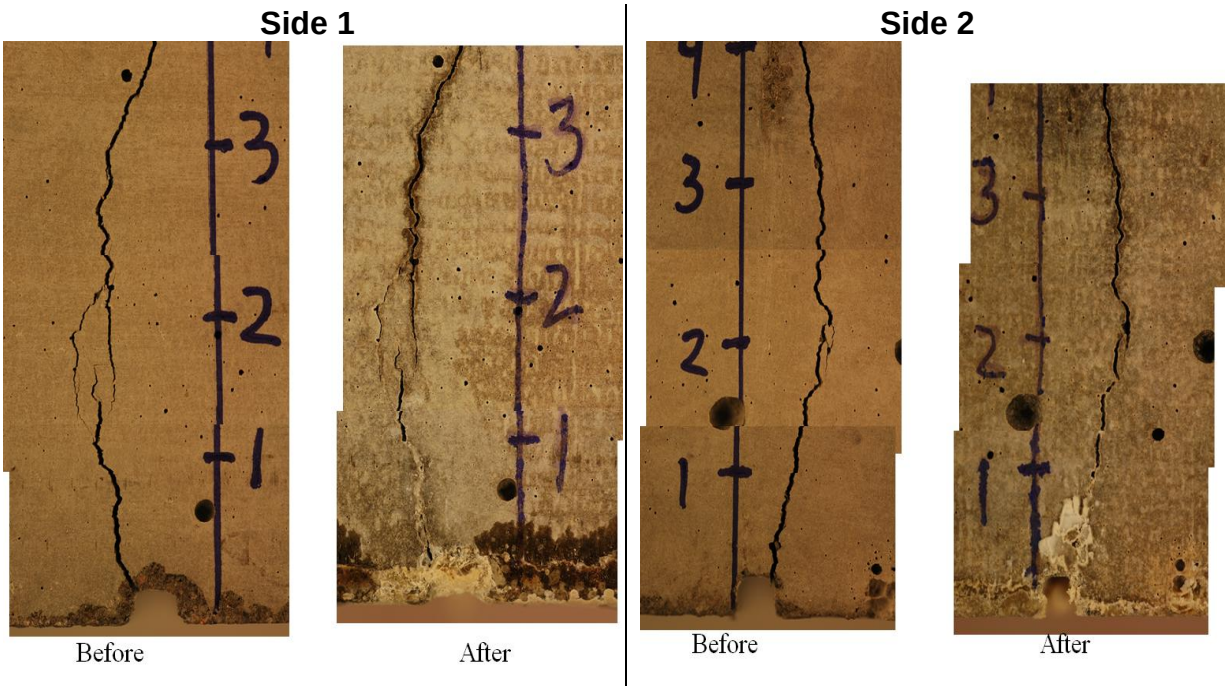

Figure A1.4: Permanently in sea water.
Crack width 0.4 mm. Cover 75 mm. Specimen H75-4-1-1

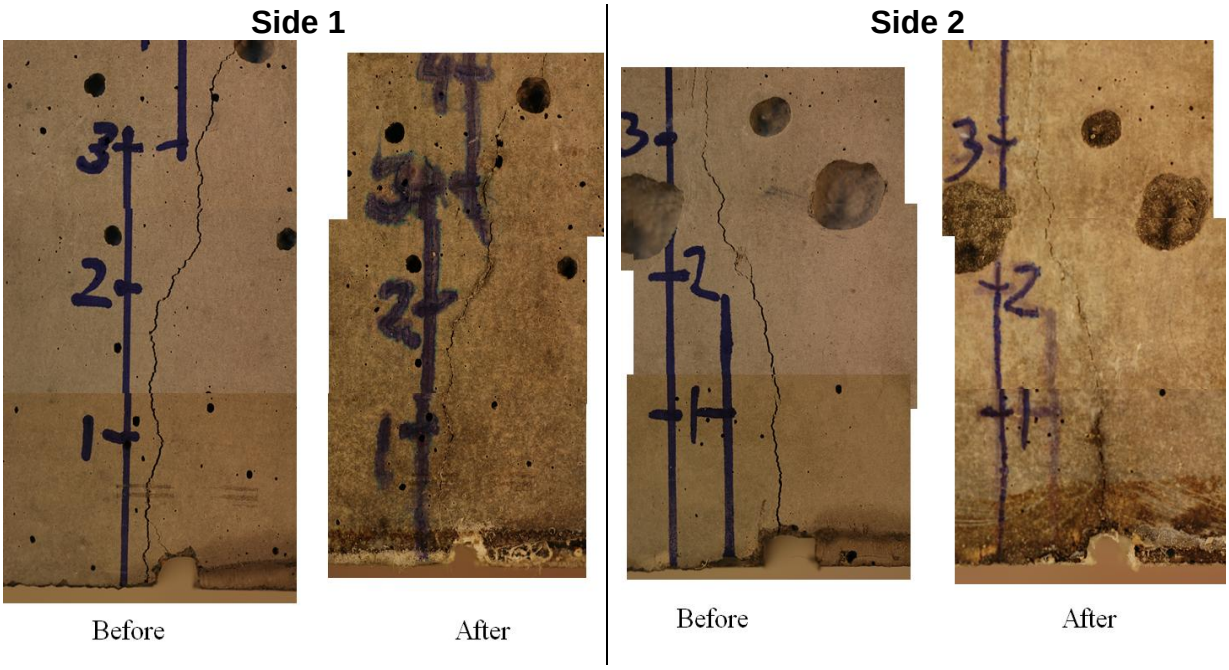

Figure A1.5: Permanently in sea water. Relaxed crack.
Crack width 0.4 mm. Cover 55 mm. Specimen H55-4R-1-1

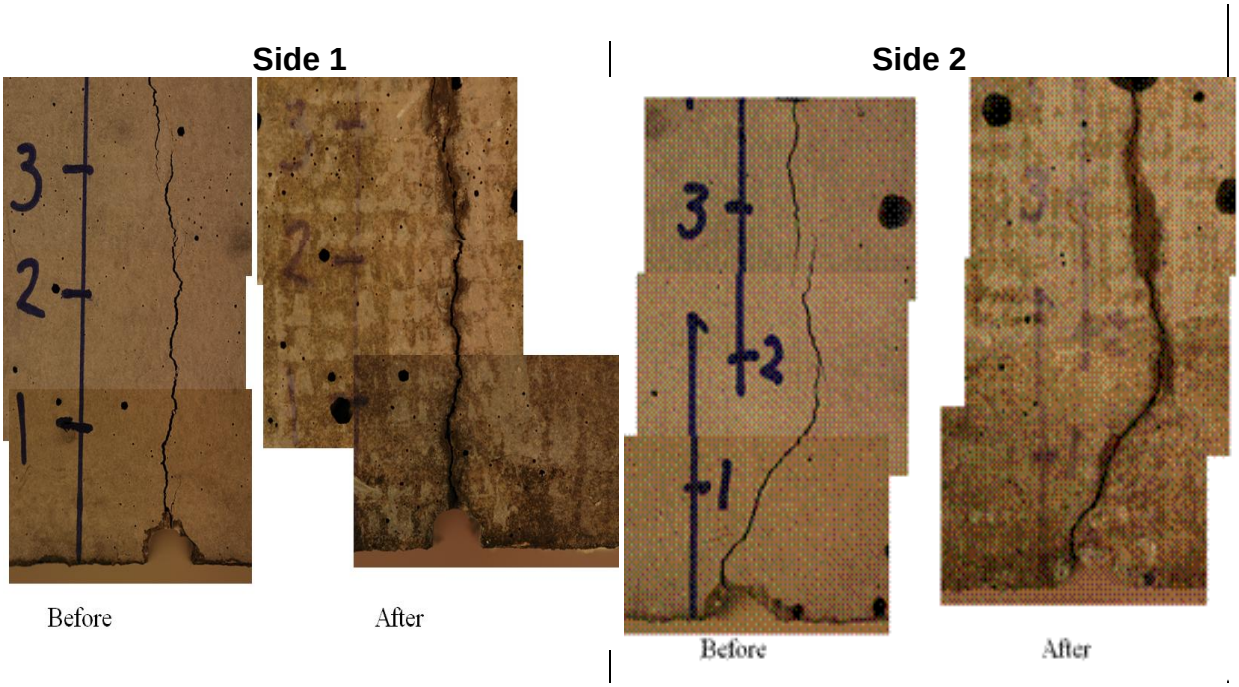

Figure A1.6: Permanently immersed in sea water. Sealed crack opening Crack width 0.2 mm. Cover 75 mm. Specimen S275-2-1-1

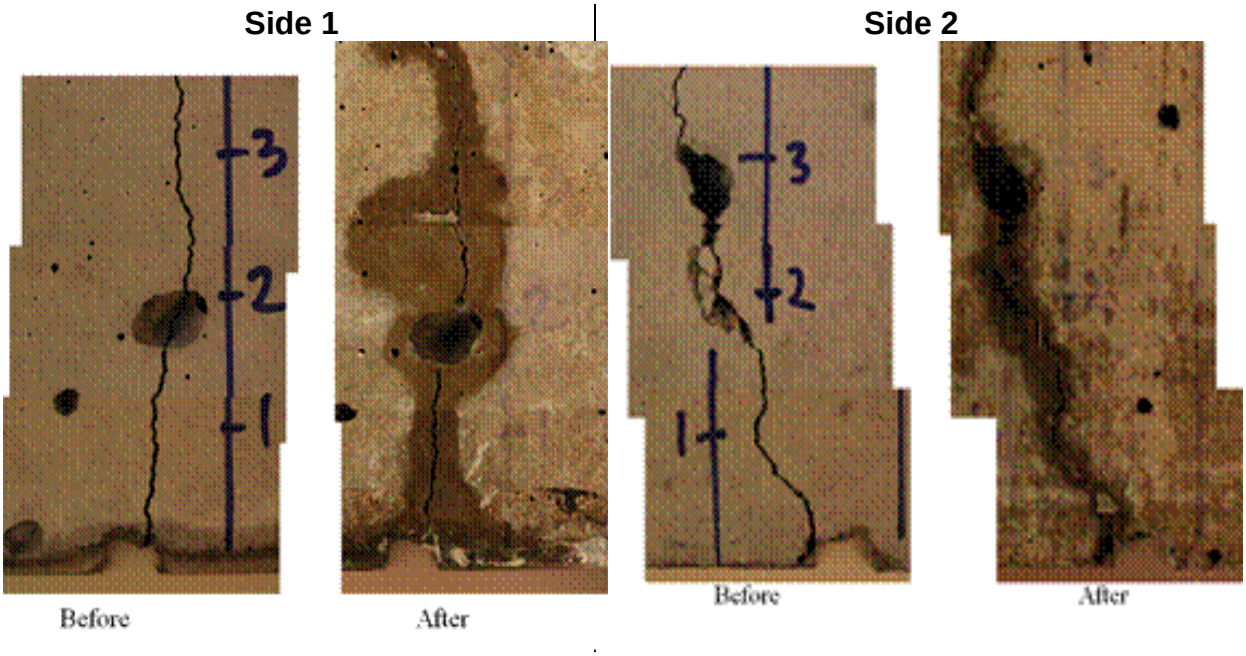

Figure A1.7: Permanently immersed in sea water. Sealed crack opening Crack width 0.4 mm. Cover 75 mm. Specimen S275-4-1-1.

A2: Specimens exposed to cyclic immersion in sea water and drying

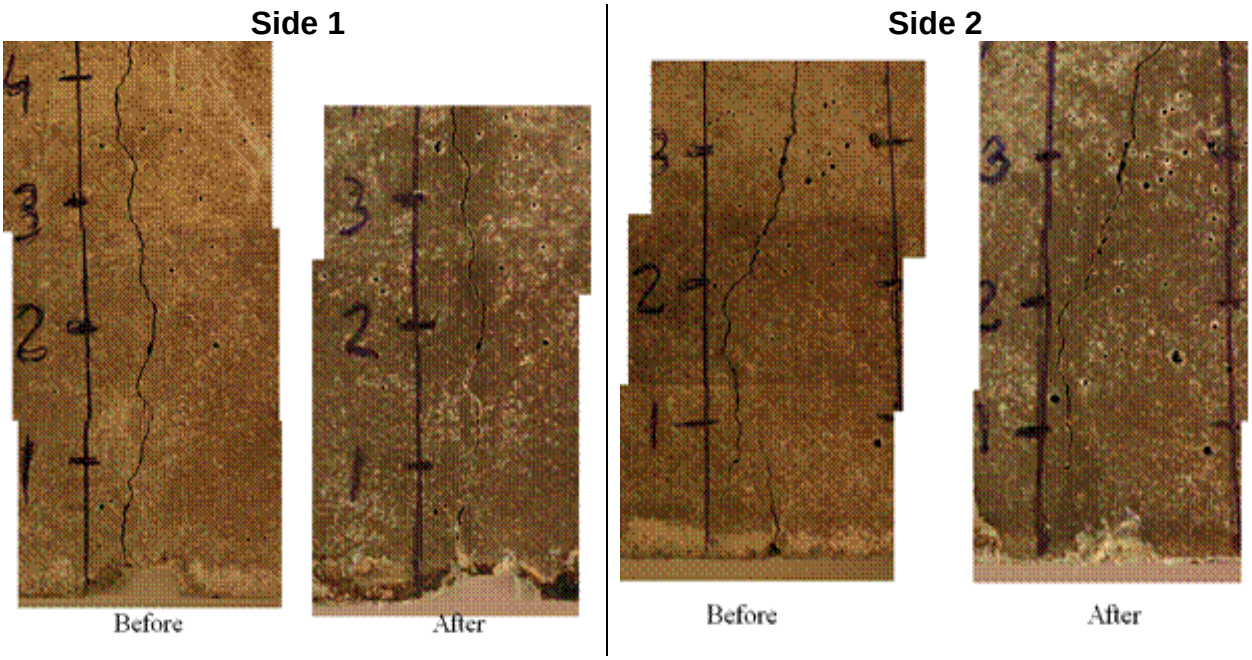

Figure A1.8: Cyclic immersion in sea water and drying.
Crack width 0.2 mm. Cover 55 mm. Specimen H55-2-2-1.

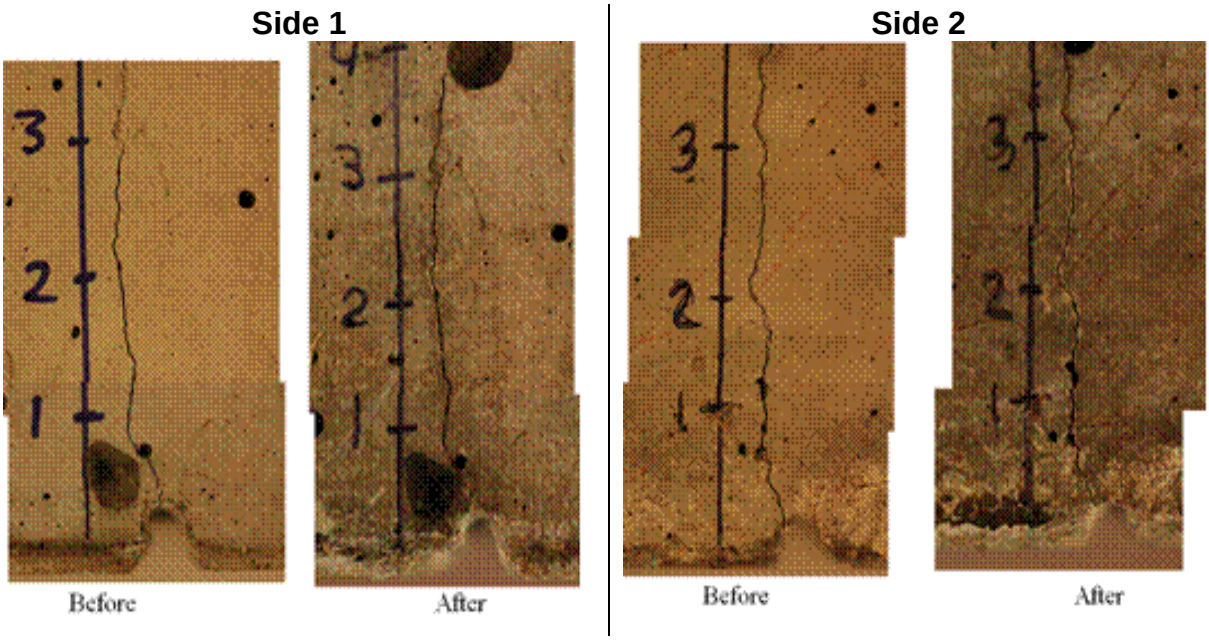

Figure A1. 9: Cyclic immersion in sea water and drying.
Crack width 0.2 mm. Cover 75 mm. Specimen H75-2-2-1.

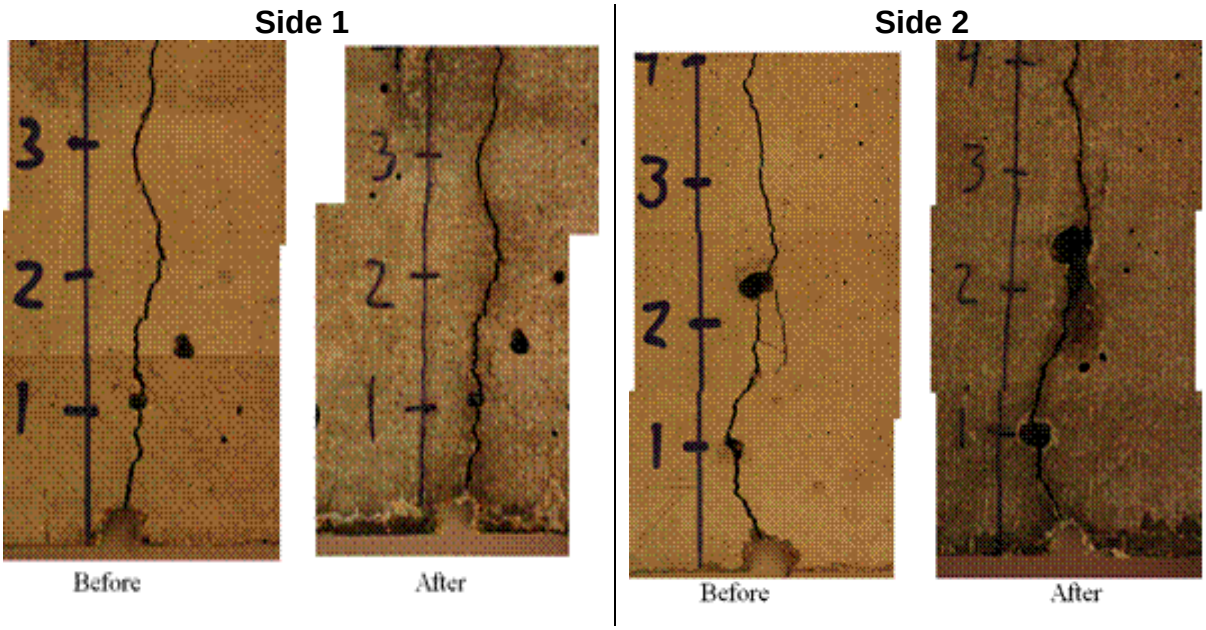

Figure A1.10: Cyclic immersion in sea water and drying.
Crack width 0.4 mm. Cover 55 mm. Specimen H55-4-2-1.

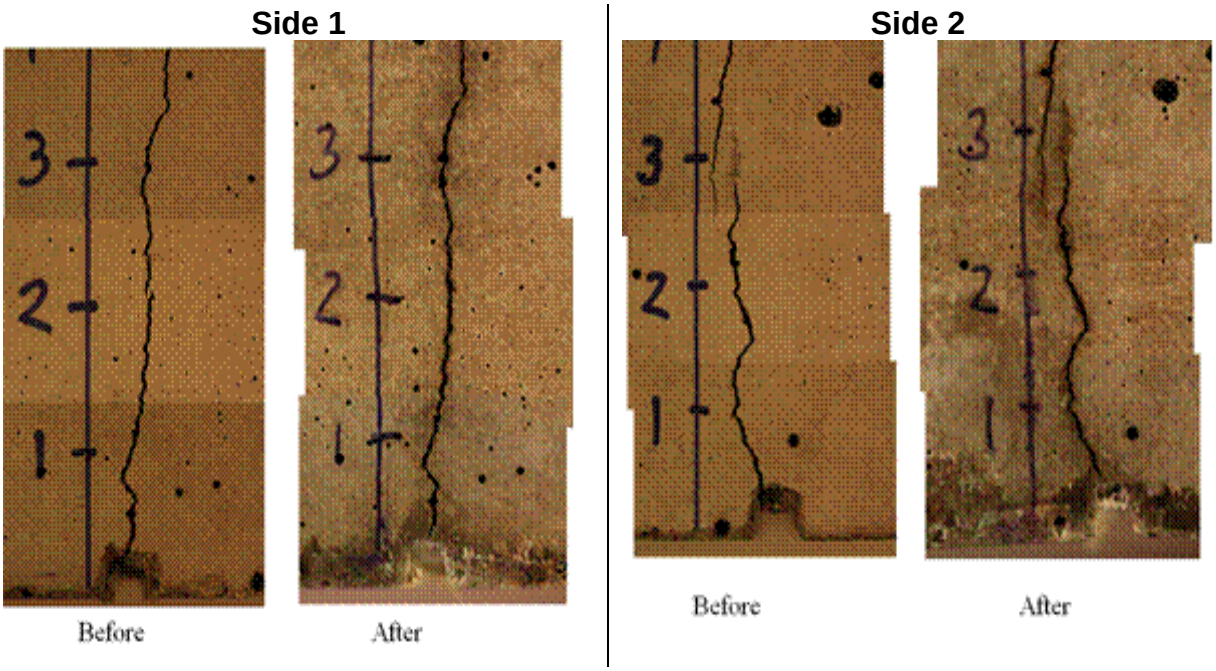

Figure A1.11: Cyclic immersion in sea water and drying.
Crack width 0.4 mm. Cover 75 mm. Specimen H75-4-2-1.

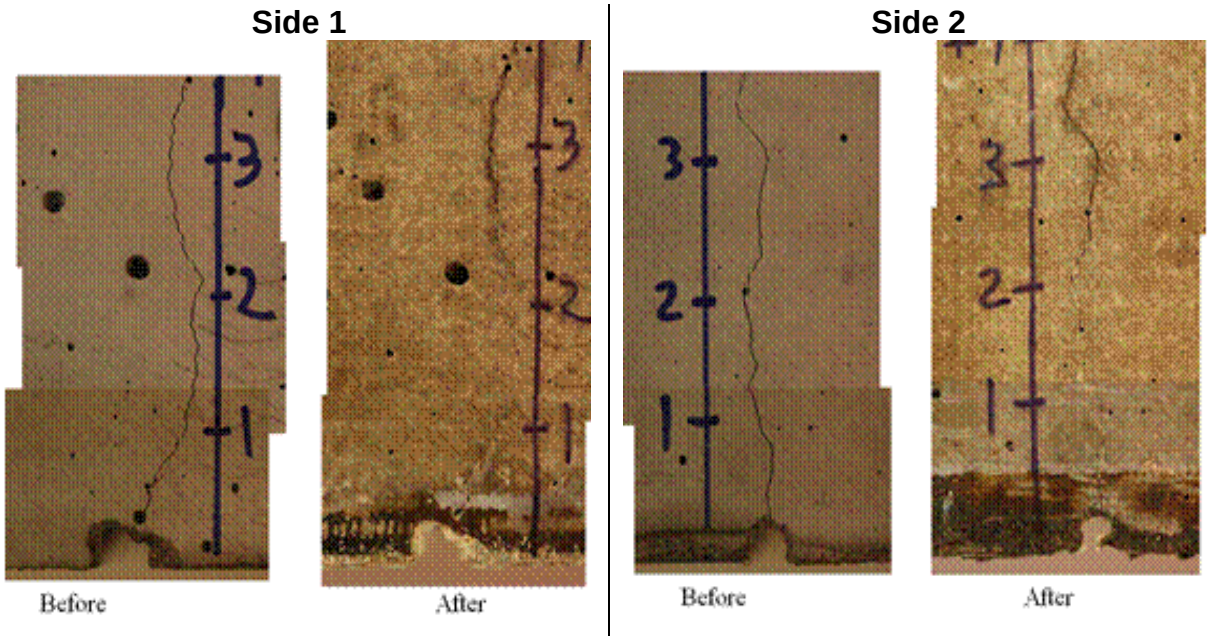

Figure A1.12: Cyclic immersion in sea water and drying. Relaxed crack. Crack width 0.4 mm. Cover 55 mm. Specimen H55-4R-2-1.

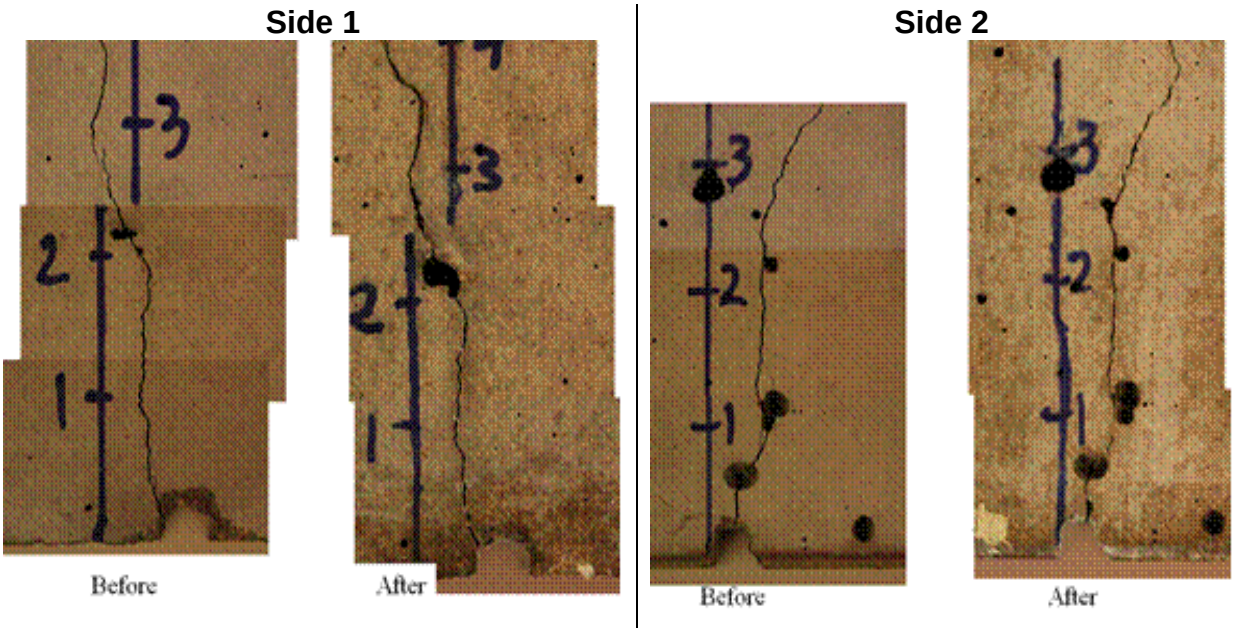

Figure A1.13: Cyclic immersion in sea water and drying. Sealed crack opening. Crack width 0.2 mm. Cover 75 mm. Specimen S275-2-2-1.

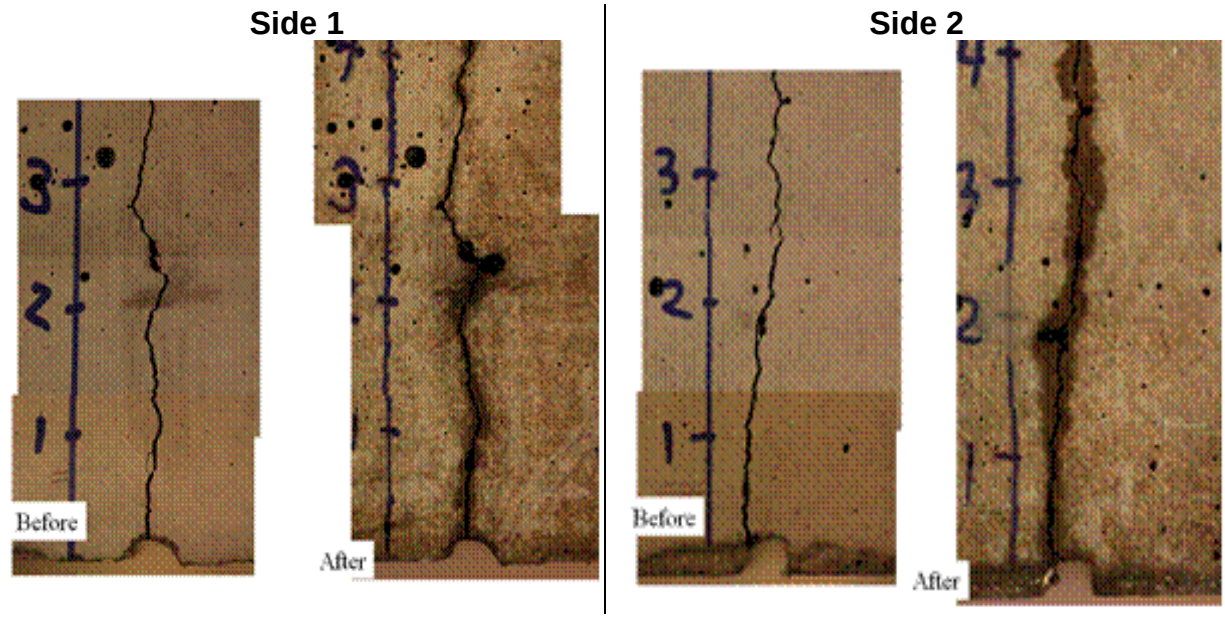

Figure A1.14: Cyclic immersion in sea water and drying. Sealed crack opening. Crack width 0.4 mm. Cover 75 mm. Specimen S275-4-2-1.

B: Specimen permanently immersed in brackish water from the Baltic Sea

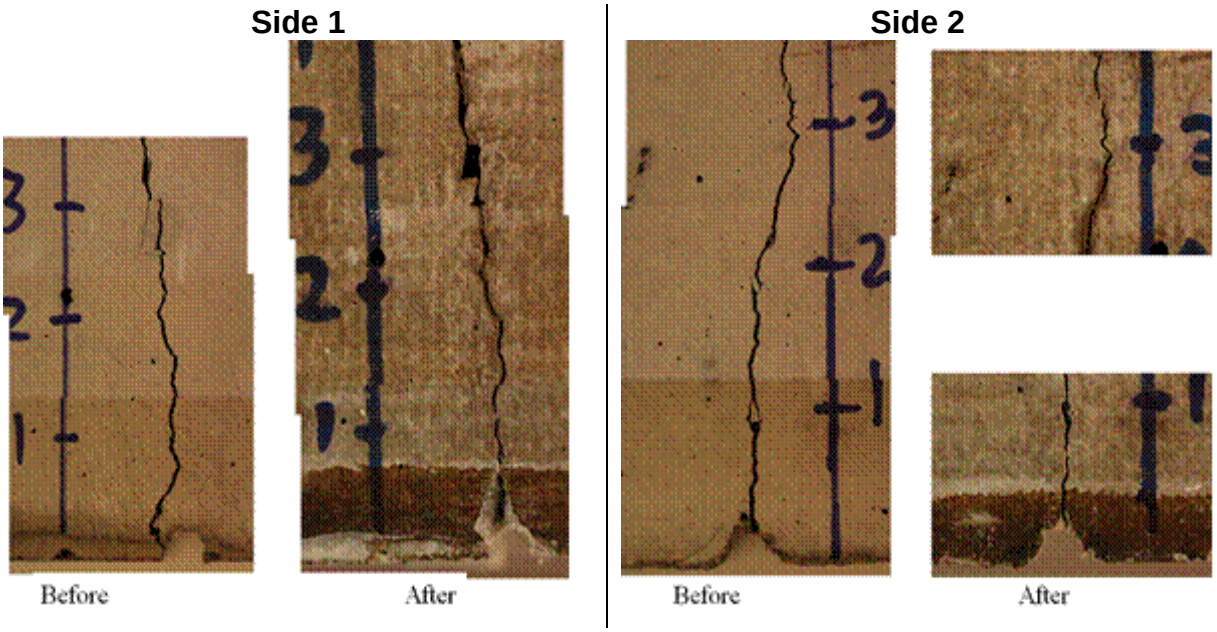

Figure A1.15: Permanently immersed in brackish water
Crack width 0.4 mm. Cover 55 mm. Specimen S155-4-1-1-Ö.

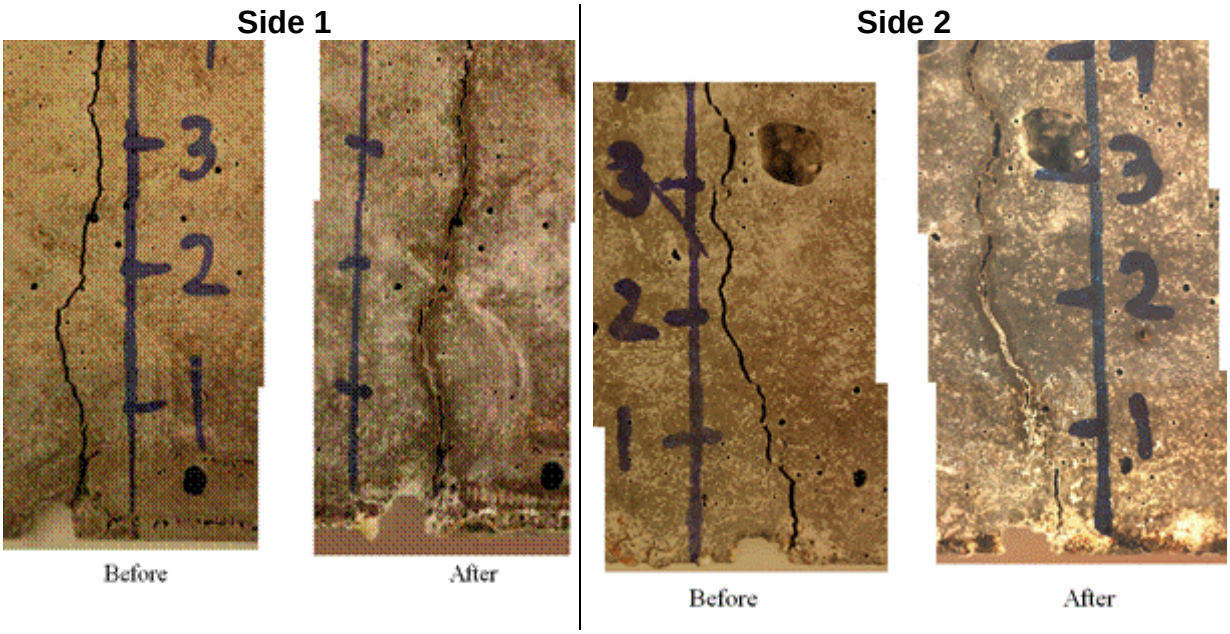

Figure A1.16: Permanently immersed in brackish water
Crack width 0.4 mm. Cover 75 mm. Specimen S175-4-1-1-Ö.

C: Specimens permanently immersed in tap water

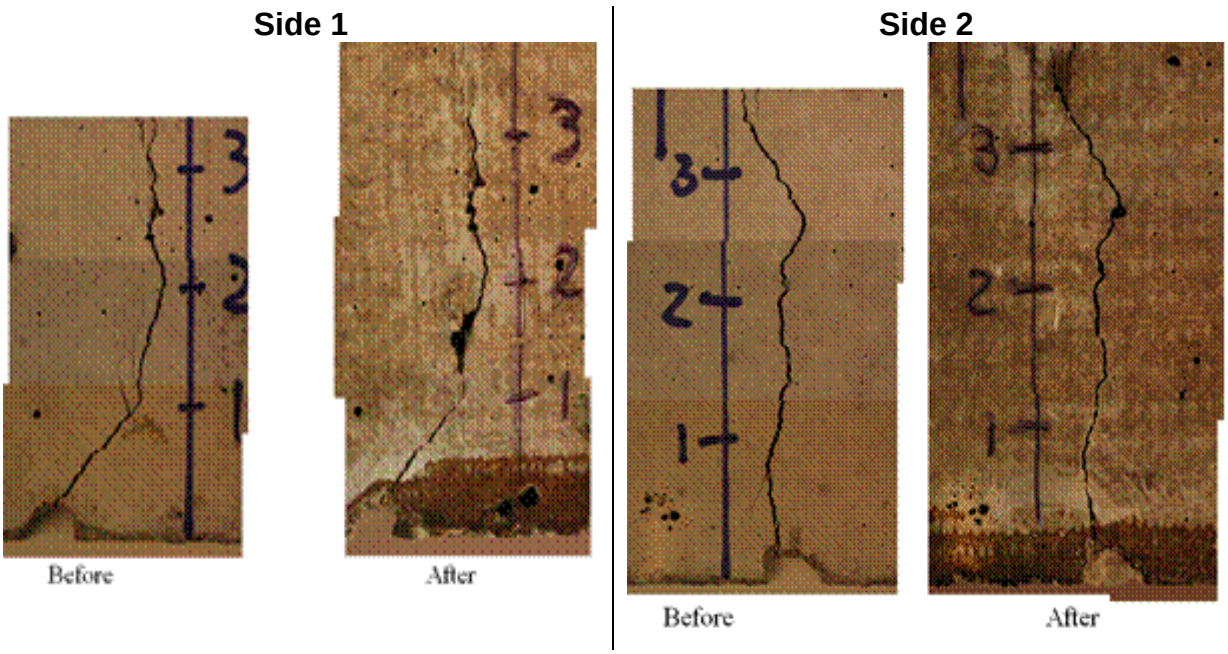

Figure A1.17: Permanently immersed in tap water
Crack width 0.4 mm. Cover 55 mm. Specimen S155-4-1-1-R.

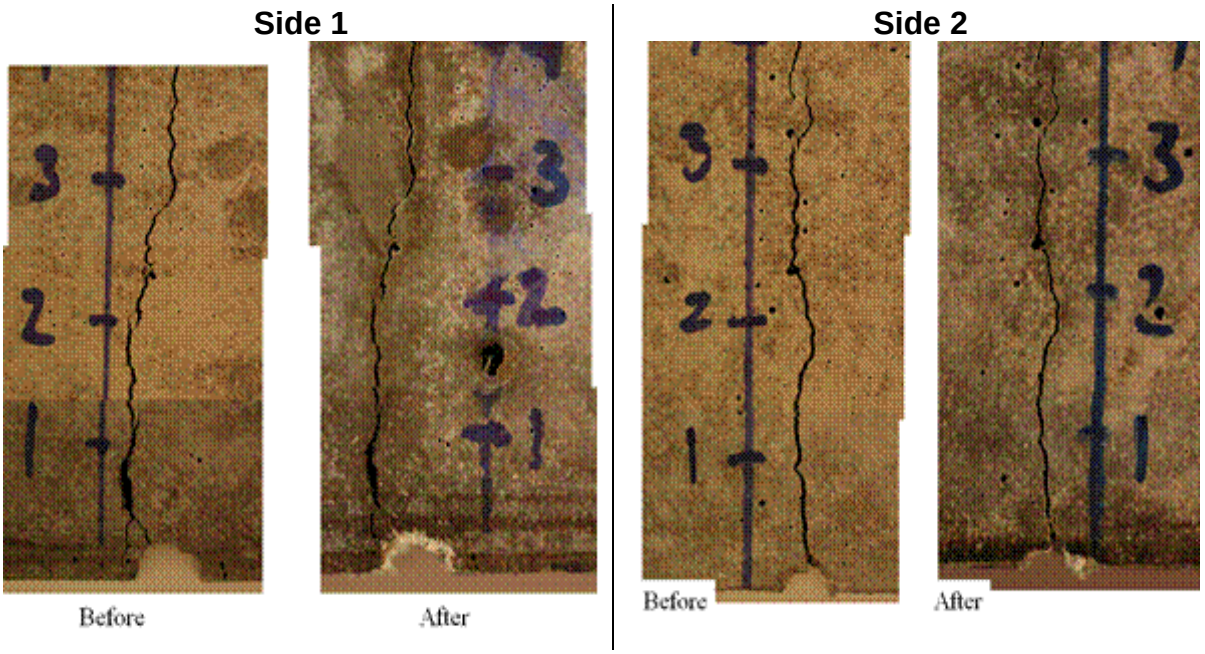

Figure A1.18: Permanently immersed in tap water
Crack width 0.0157 in. Cover 75 mm. Specimen S175-4-1-1-R.

APPENDIX 2

Photographs of the crack on about 3 cm depth after terminated exposure

Photographs of the lower part of the crack for the same specimens are shown in figures 7.2 - 7.11 in the main text

Figure A2.1: 0.2 mm crack after 1 year permanent immersion in sea water.
Test series 1, specimen H75-2-1-1.

Figure A2.2: 0.4 mm crack after 1 year permanent immersion in sea water.
Test series 1, specimen H75-4-1-1.

Figure A2.3: 0.2 mm crack after 1 year cyclic immersion in sea water and drying. Test series 1, specimen H75-2-2-1.

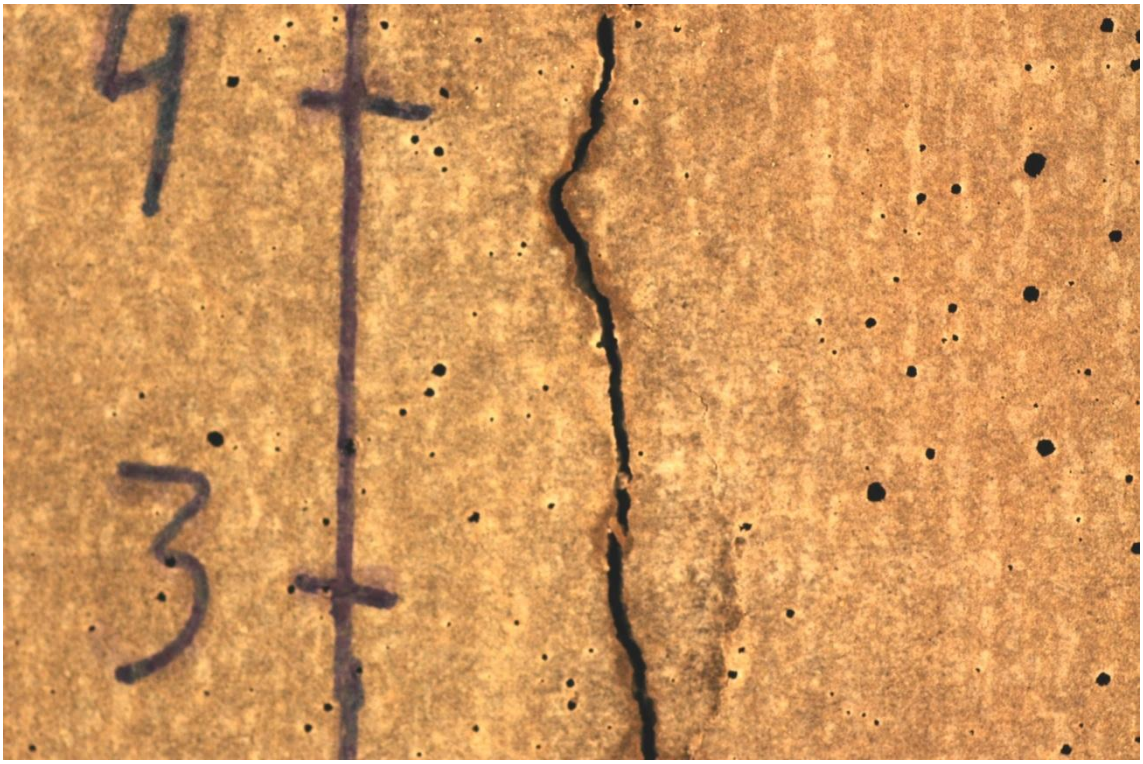

Figure A2.4: 0.4 mm crack after 1 year cyclic immersion in sea water and drying. Test series 1, specimen H75-4-2-1.

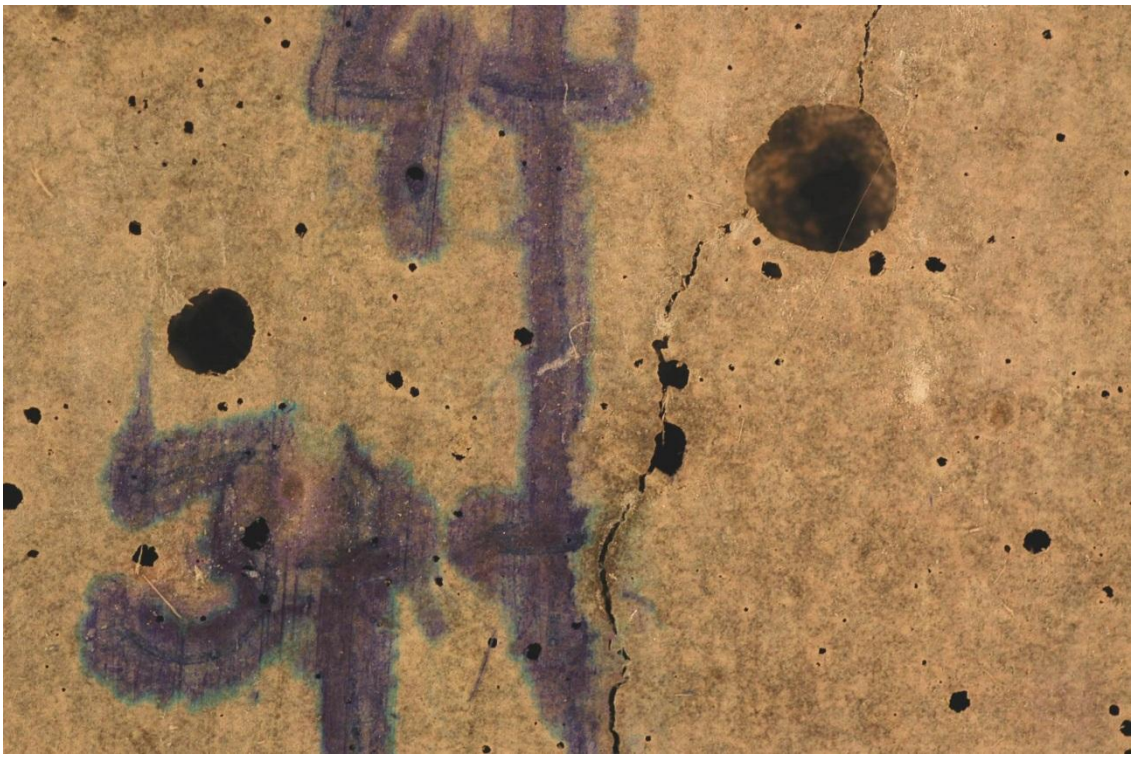

Figure A2.5: 0.4 mm relaxed crack after 1 year permanent immersion in sea water. Test series 1, specimen H55-4R-1-1.

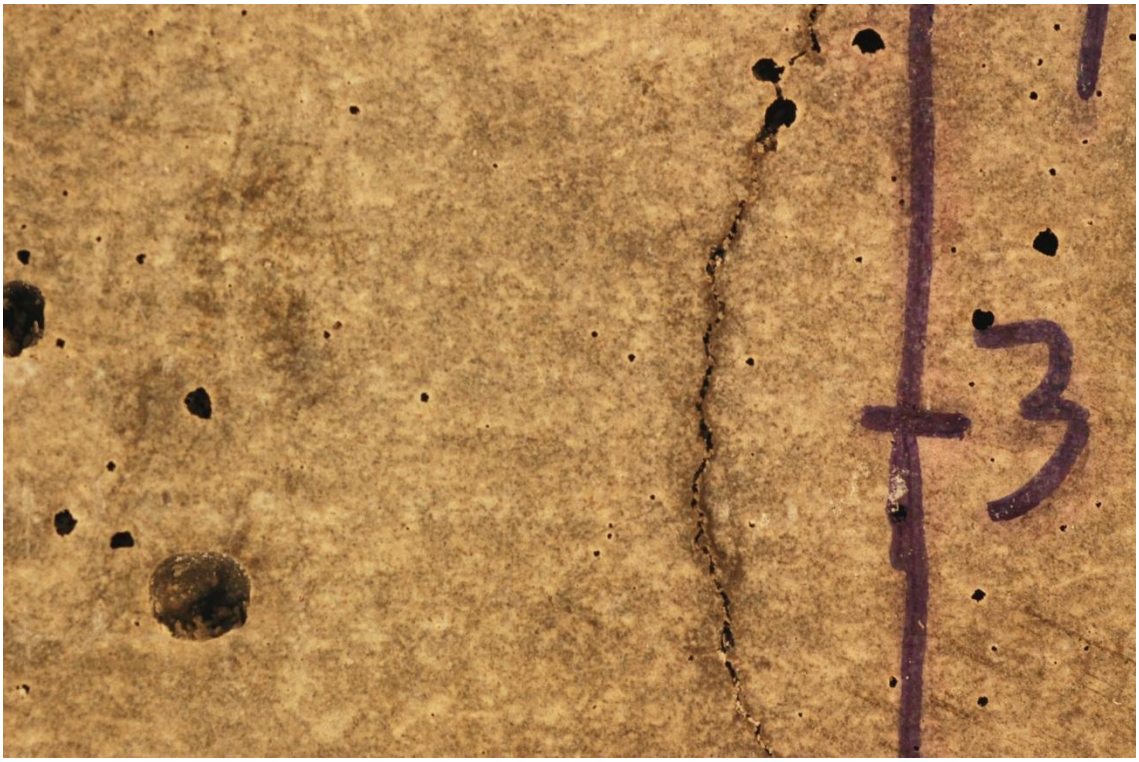

Figure A2.6: 0.4 mm relaxed crack after 1 year cyclic immersion in sea water and drying. Test series 1, specimen H55-4R-2-1.

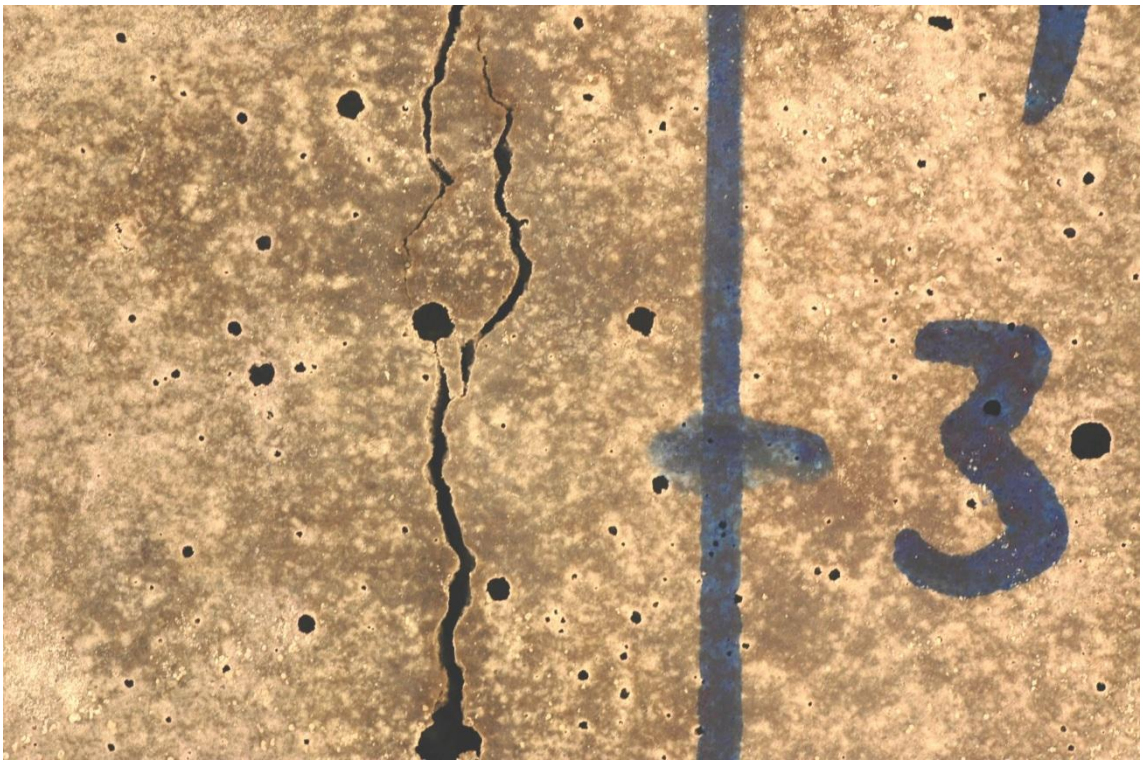

Figure A2.7: 0.4 mm crack after 1 year permanent immersion in pure water.
Test series 3, specimen S175-4-1-1-R.

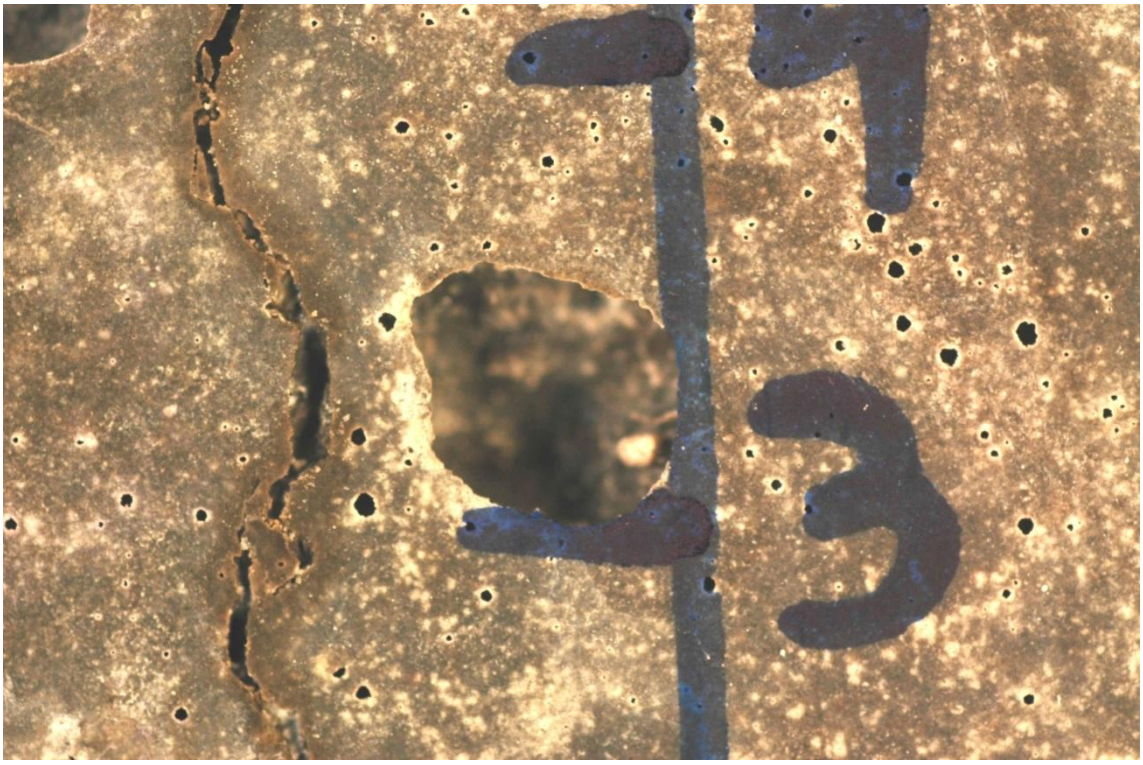

Figure A2.8: 0.4 mm crack after 1 year permanent immersion in brackish water.
Test series 2, specimen S175-4-1-1-Ö.

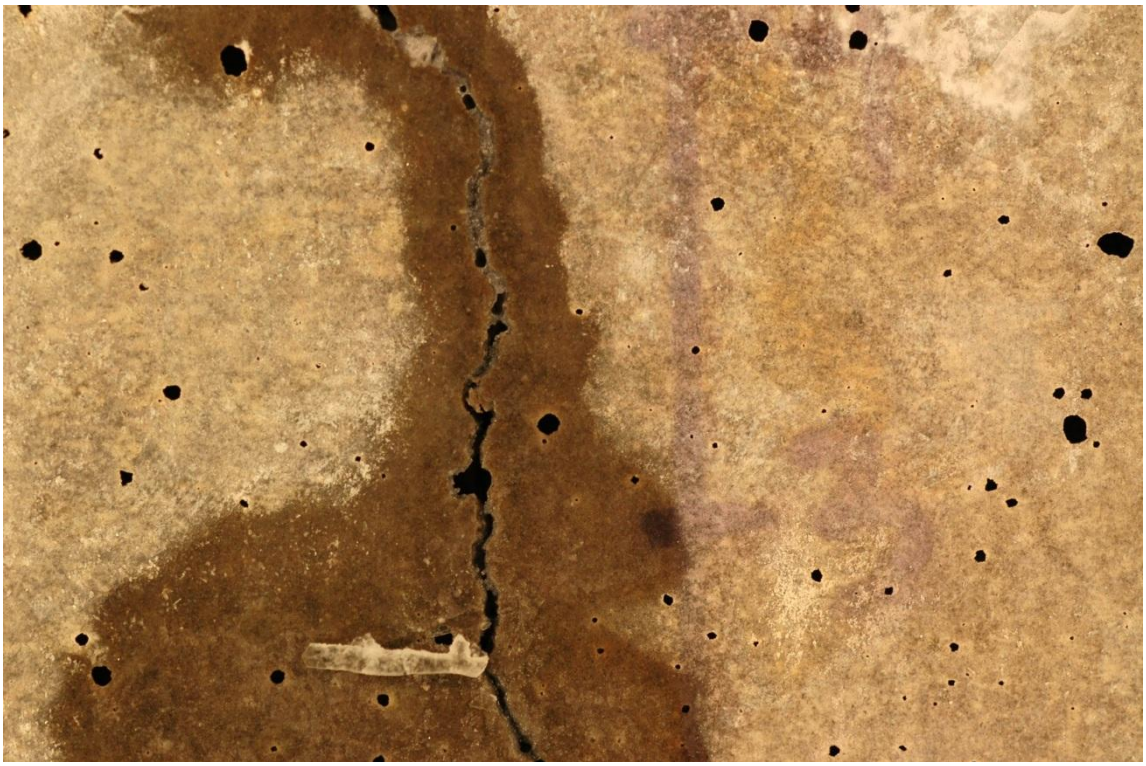

Figure A2.9: 0.4 mm sealed crack after 1 year permanent immersion in sea water. Test series 5, specimen S275-4-1-1.

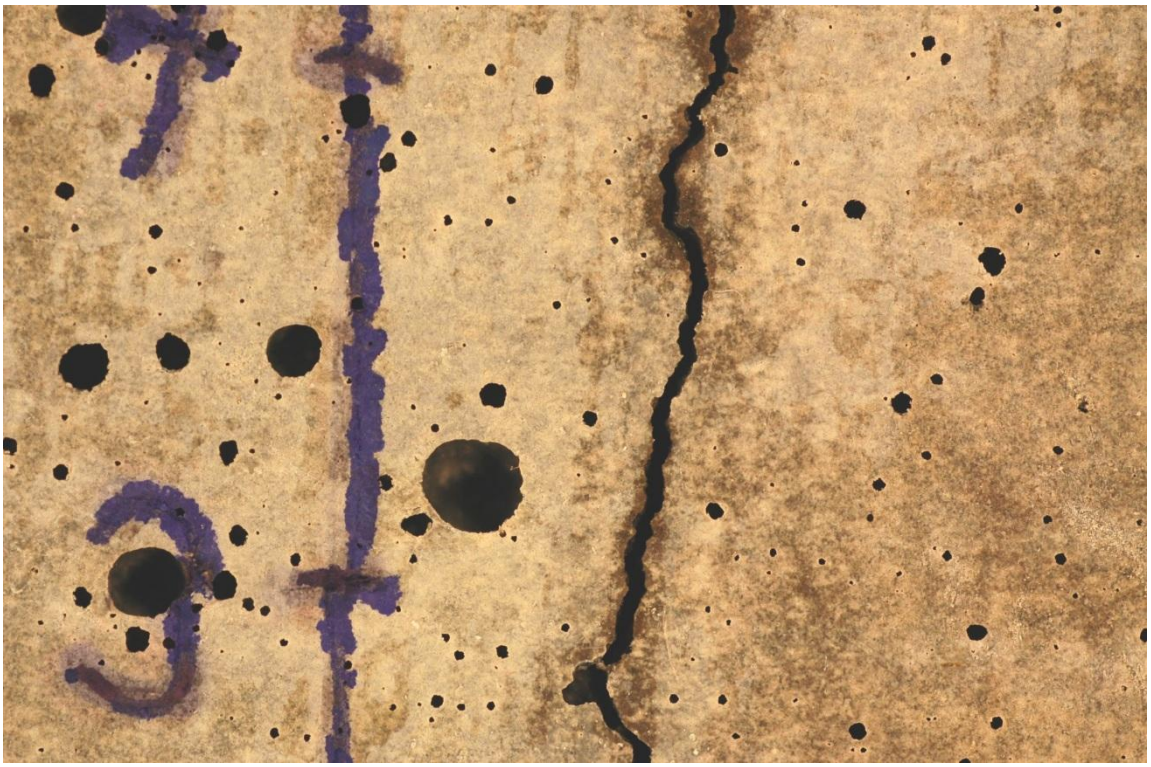

Figure A2.10: 0.4 mm sealed crack after 1 year cyclic immersion in sea water and drying. Test series 5, specimen S275-4-2-1.

APPENDIX 3

Element composition of precipitations in cracks

Data from Kalinowski & Fjällberg (2010)

Table A3.1: 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	78-91% CaO 2-10% MgO 4-8% SiO_2	H55-2-1-1 Fig 14.2
			Needles	11-13% Al_2O_3 14% SiO_2 14% SO_3 55% CaO	
		55 mm [2)]	Big crystals	98% CaO	
			Small needles	2% Al_2O_3 33% SiO_2 55% CaO	
	0.4 mm	5 mm [3)]	Crystals	69% MgO 15% SiO_2 11% CaO	H55-4-1-1 Fig 14.2
		55 mm [4)]	Needles	11% Al_2O_3 14-16% SiO_2 15% SO_3 55% CaO	
			Crystals (plates)	90% CaO	
	0,4 mm Relaxed crack	5 mm [5)]	Needles	6-15% Al_2O_3 1-10% MgO 3-12% SiO_2 8-22% SO_3 51-82% CaO	H55-4R-1-1 Fig 14.2
			Crystals (plates)	98% CaO	
		55 mm [6)]	Crystals	92-97% CaO	
75 mm	0,2 mm Sealed crack opening	5 mm [7)]	Plates	91-97% CaO	S275-2-1-1 Fig 14.2
			Plates	18-36% Al_2O_3 1-8% SiO_2 0% SO_3 52-60% CaO	
		55 mm [8)]	Plates	98% CaO	
	0,4 mm Sealed crack opening	5 mm [9)]	Plates	85-99% CaO	S275-4-1-1
			Small plates	32% Al_2O_3 5-9% SiO_2 56-60% CaO	
		55 mm [10)]	Plates	95-99% CaO	

Comments from Kalinowski & Fjällberg (2010) are cited below.

1) "Calcite crystals with prismatic shape, size to 50x10 μm. Needle-shaped sulphates of unspecified composition"

2) "Big amount of $Ca(OH)_2$-crystals with size of about 0.5 mm"

3) "Small amount of $Mg(OH)_2$-crystals (size about 20 μm)"

4) "Comparably small amount of big $Ca(OH)_2$-crystals (size up to 0.5 mm). Needle-shaped crystals of unspecified sulphates"

5) "$Ca(OH)_2$-crystals as single small prismatic prisms (size about 100 μm) and bigger crystal aggregates. $Ca(OH)_2$ also exists in the shape of fine-grained coating (aggregate of very small needle-shaped crystals). Precipitation of ettringite and other unspecified sulphates"

6) "Very abundant presence of plate-shaped $Ca(OH)_2$-crystals (size to 1 mm). No sulphates"

7) "$Ca(OH)_2$ in the shape of big plates (to 1 mm). Hexagonal plate-shaped crystals of Ca-aluminate. No ettringite"

8) "$Ca(OH)_2$ as big plates (to 1 mm)"

9) "Big amount of $Ca(OH)_2$, mostly as small grains with irregular shape. A small amount of single hexagonal flat crystals of Ca-aluminate"

10) " Comparably low amount of $Ca(OH)_2$-crystals (much less than on depth 5 and 25 mm). $Ca(OH)_2$ exhibits itself as big plates, smaller prismatic crystals and grains with irregular shape"

Table A3.2: Element composition of precipitations in cracks.
Specimens cyclically exposed to sea water and air.

Cover	Crack width	Depth	Type of precipitation	Elements	Specimen
55 mm	0.2 mm	5 mm [1)]	Small crystals	10-14% MgO 4-6% SiO_2	H55-2-2-1
				77-80% CaO	
			Dark fine-grained "mass"	76% MgO 8-10% SiO_2 11% CaO	
		55 mm [2)]	Plates	92% CaO 6% SiO_2	
			Needles	11% Al_2O_3 16% SiO_2 16% SO_3 56% CaO	
	0.4 mm	5 mm [3)]	Needles type 1	2-7% MgO 91-96% CaO	H55-4-2-1
			Needles type 2	64-92% MgO 2-5% SiO_2 3-33% CaO	
			Plate	96% CaO	
		55 mm [4)]	Big crystals	93-96% CaO	
	0,4 mm Relaxed crack	5 mm [5)]	Needles/crystals	10-19% MgO 80-90% CaO	H55-4R-2-1
			"Mat" of short needles	56-69% MgO 0-2% Al_2O_3 3-20% SiO_2 4-42% CaO	
		55 mm [6)]	Needles	16% Al_2O_3 4% SiO_2 25% SO_3 54% CaO	
			Big plates	98% CaO	

Comments from Kalinowski & Fjällberg (2010) are cited below.

1) "Very fine-graded $Mg(OH)_2$ (brucit) appears macroscopically as a bluish coating. No sulphates"

2) "Mainly $Ca(OH)_2$-crystals and needles of ettringite and unspecified sulphates"

3) "Very fine-graded brucit. Small bundles of elongated crystals of Ca-carbonate and Ca-hydroxide"

4) "Abundant amount of crystals of Ca-carbonate"

5) "Fine-graded coating of brucit (aggregate of of small needle-shaped crystals). Bigger grains of $Ca(OH)_2$ or Ca-carbonate with irregular shape"

6) "Big amount of $Ca(OH)_2$-crystals (size of individual crystal to 200 μm. Size of crystal aggregate to 500 μm). Relatively small amount of needle-shaped ettringite crystals"

Table A3.3: 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)]	Prismatic crystals	97-99% CaO 1-2% SiO_2	S155-4-1-1-R Fig 14.4
			Thin cover	96% CaO 3% SiO_2	
		55 mm [2)]	Needles	17 % Al_2O_3 3% SiO_2 25% SO_3 54% CaO	
			Small needles	1% SiO_2 98% CaO	
			Big plates	92-98% CaO	

Comments from Kalinowski & Fjällberg (2010) are cited below.
1) "$Ca(OH)_2$ as prismatic crystals and thin coating. No ettringite"
2) "Big plate-shaped crystals of $Ca(OH)_2$ (size to 1 mm). Small amount of needle-shaped ettringite crystals"

Table A3.4: 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)]	Needles	12-15% Al_2O_3 6-17% SiO_2 15-22% SO_3 56% CaO	S155-4-1-1-Ö
			Small cubes	5%SiO_2 93% CaO	
			Plates	98% CaO	
		25 mm [2)]	Needles	14-16% Al_2O_3 3-10% SiO_2 21% SO_3 53-60% CaO	
			Big plates	2-7% SiO_2 93-97% CaO	
		55 mm [3)]	Big plates	5% SiO_2 94% CaO	

Comments from Kalinowski & Fjällberg (2010) are cited below.
1) "Abundant amount of needle-shaped ettringite crystals. $Ca(OH)_2$ as small cube-shaped crystals. Small amount of unspecified sulphates"
2) "Big plate-shaped of $Ca(OH)_2$ (size to 1 mm). Needle-shaped crystals of ettringite (smaller amount than on 5 mm deep) and other unspecified sulphates"
3) "Big plate-shaped crystals of $Ca(OH)_2$. Very small amount of ettringite and Ca Al S-needles"