NTNU/MTP REPORT

NTNU

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TITLE:

HERØY F&U

WP2.A4 "Corrosion mechanism including effect of environmental parameters"

Summary of work and findings

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ABSTRACT:

This report contains a summery of results from literature reviews, inspections and two MSc thesis to investigate the effect of pH, chlorides, sulphate and oxygen on corrosion of tensile wires inside ducts in concrete bridges.

The following observations were done in the experimental work:

1. pH, chloride and sulphate are important environmental parameters for corrosion on tensile wires inside a duct.
2. A change of pH from 12.5/13 to <11, resulted in strong increase in corrosion on the wires.
3. Test in electrolytes simulating fluids inside a duct and exposed in contact with air, will react with the atmosphere and reduce the pH below 11.
4. The effect of oxygen on corrosion is not thourougly examined and no clear conclusion can be drawn.
5. The possible effect of galvanic corrosion between wires without concrete and with concrete coverage needs to be furher investigated.

The conclusion from the work is summarised in Chapter 3 and proposal for further work in Chapter 4.

01	02.01.2025	For use	Roy Johnsen	
REV.	**DATE**	**REASON FOR ISSUE**	**PREPARED BY**	**APPROVED**

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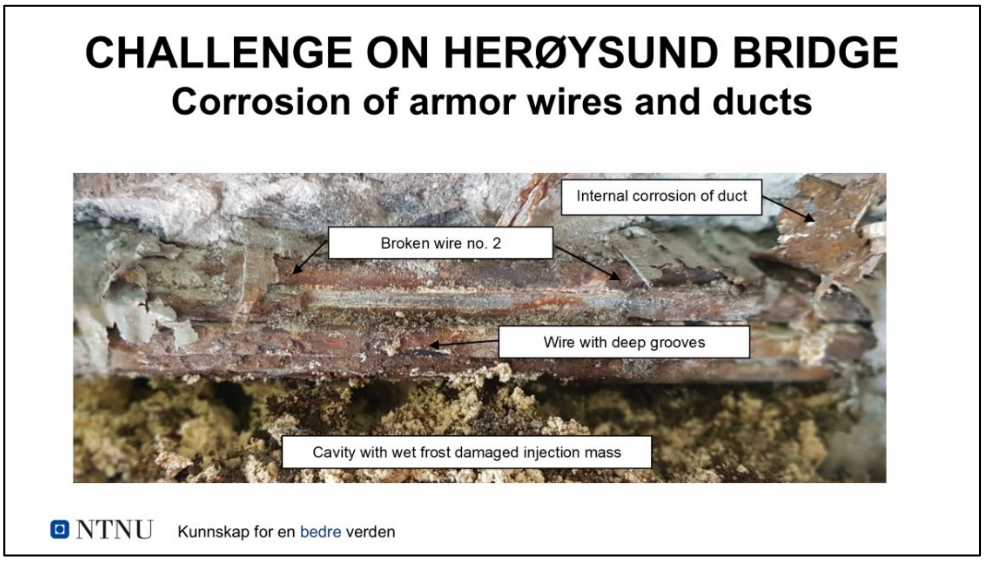
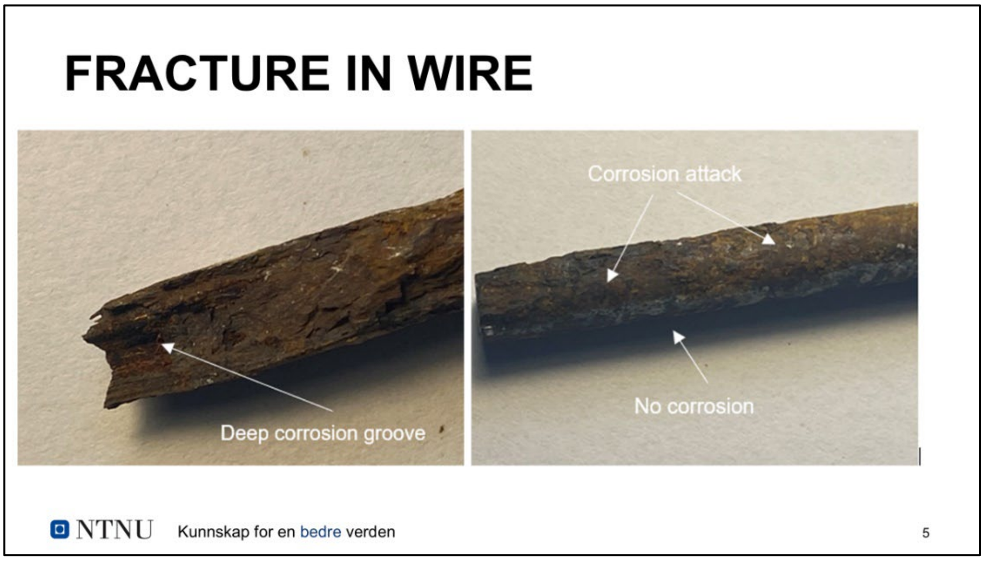
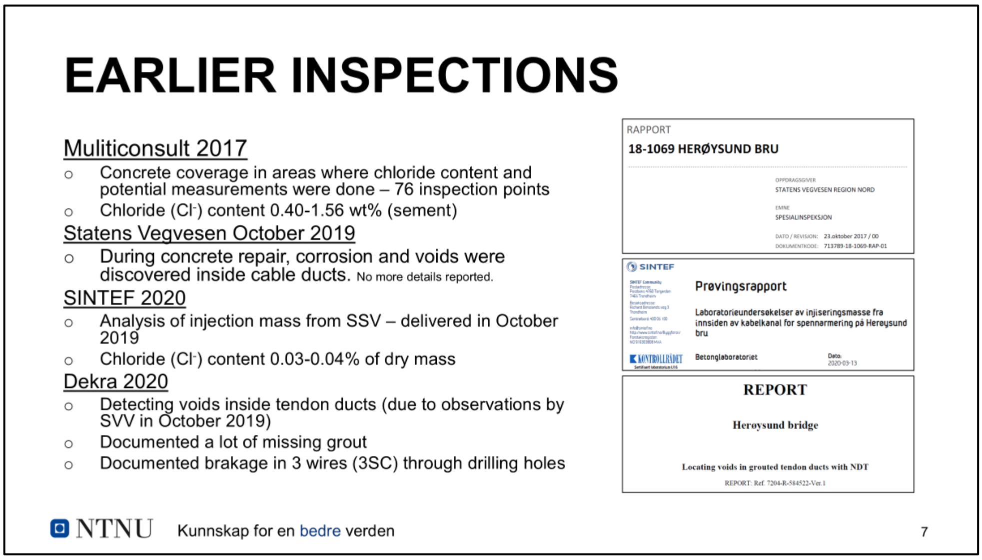
1 WORK PERFORMED BEFORE START-UP OF THE HERØY FOU PROJECT[1-2,4]

This report contains a summery of the work performed in WP2.A4. More details are given in the reports[1-5].







EARLIER INSPECTIONS, cont.

SVV and NTNU August 2020

- Drilled holes in three different locations – selected from the Decra results with indication of missing grout.
- Several holes in the concrete drilled to expose the cable duct and wires
- Injection mass (SINTEF analysis), part of broken wire from two positions collected and photos taken.

SINTEF 2020

- Analysis of injection mass
- Low chloride content in solid 0.035% and pH 13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HERØYSUND BRU
Korrosjon av spennarmering i betongbruer

Roy Johnsen

Statens Vegvesen

90599200-01 | 90599200 | 46/14


SINTEF

Prøvingsrapport

Undersøkelser av injiseringsmasse fra kabelkanal til Herøysund bru

Dato: 2020-11-30

2020/Location 1, Kabelbane 2 (close to 2SA-2)

Analysis of injection mass:

- Cl⁻: 0.035%
- Moist: 21%
- pH: 13 (measured with pH paper)

Corrosion observations

- Corrosion on wires – indication of more attacks in the bottom
- Injection mass covers the gap and partly the surface of the wires
- Part of the duct volume not filled with injection mass
- Consistens of injection mass varies from dry to frost damaged

2020/Location 3, Kabelbane 2 (close to 2SA-2)

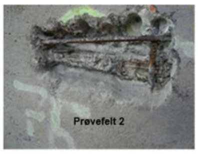
Analysis of injection mass:

- Cl⁻: 0.037%
- Moist: 44% (wet)
- pH: 13 (measured with pH paper)

Corrosion observations

- Serious corrosion on wires, more in the bottom
- One broken wire found (investigated)
- No external corrosion on duct
- «Damaged» injection mass

2020/Location 2, Kabelbane 2, but North side of the bridge



Corrosion observations
- Serious corrosion on wires, more in the top
- Sroius corrosion of the duct
- Injection mass partly covered the wires and the gap between the wires
- One wire cut and analysed in the lab

Analysis of injection mass:
- Cl-: ?
- Moist: ?
- pH: ?

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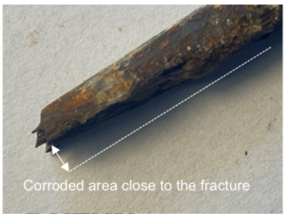
FRACTURED WIRES
From inspection August 2020 – Inspection point 3



Corrosion observations
- Fracture in wire no. 2 from top
- Corrosion on the wire on both side of the fracture
- Min. wire diameter close to the fracture 2.9 mm
- Only part of the wire diameter exposed to corrosion
- At fracture: 30-35% of the cross section intact

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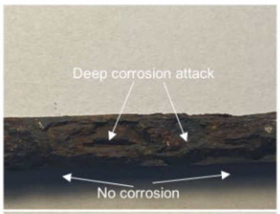
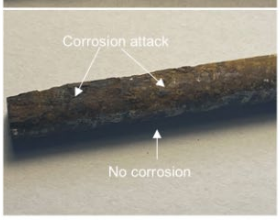
FRACTURED WIRES
From inspection August 2020 – Inspection point 1





Corrosion observations
- No fracture had occured in this wire
- Deep corrosion grooves in the wire – oval form with length 5-15 mm, depth 1.5 mm snd width 3-4 mm
- All grooves were on the same side of the wire, while the rest of the wire surface was without and serious attacks.

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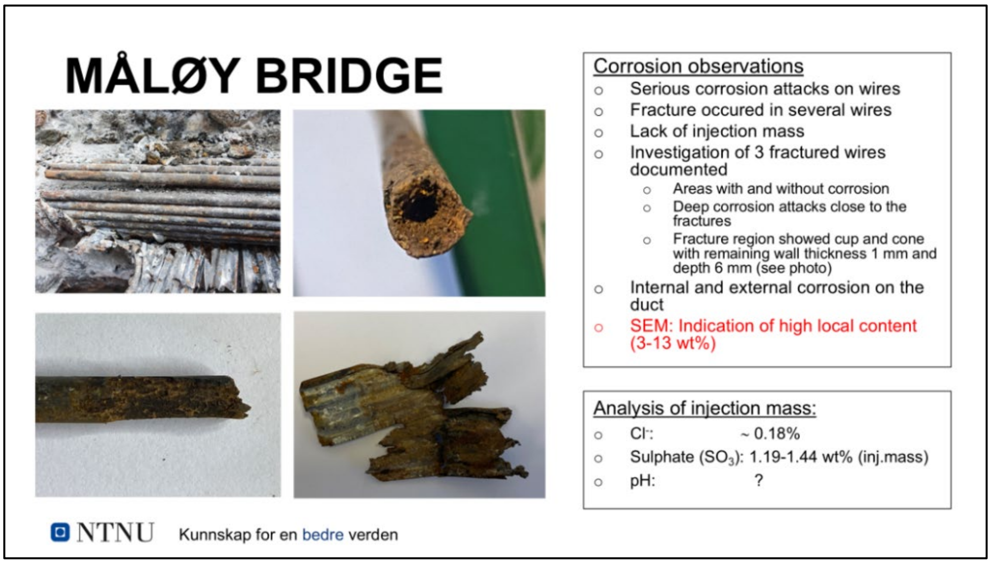
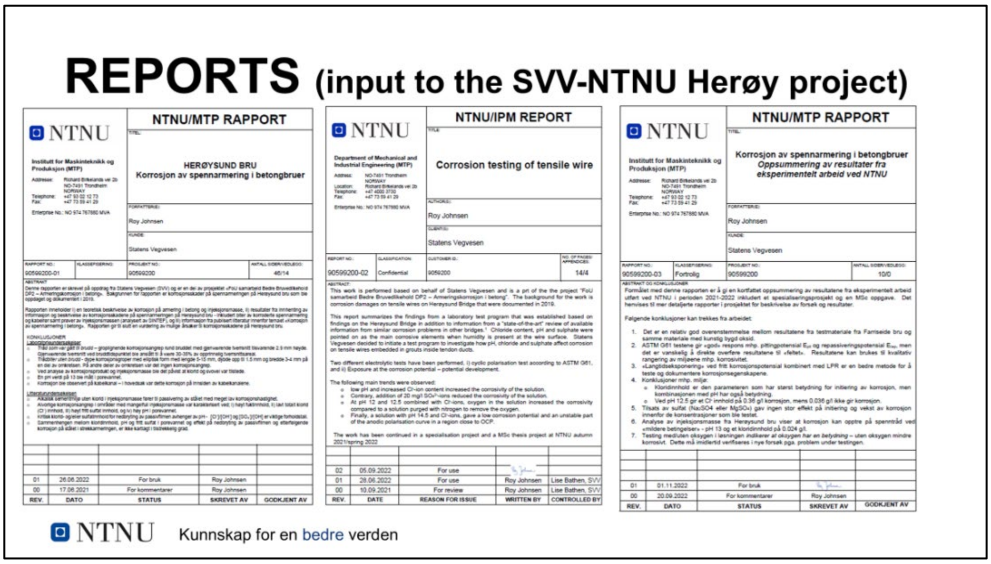
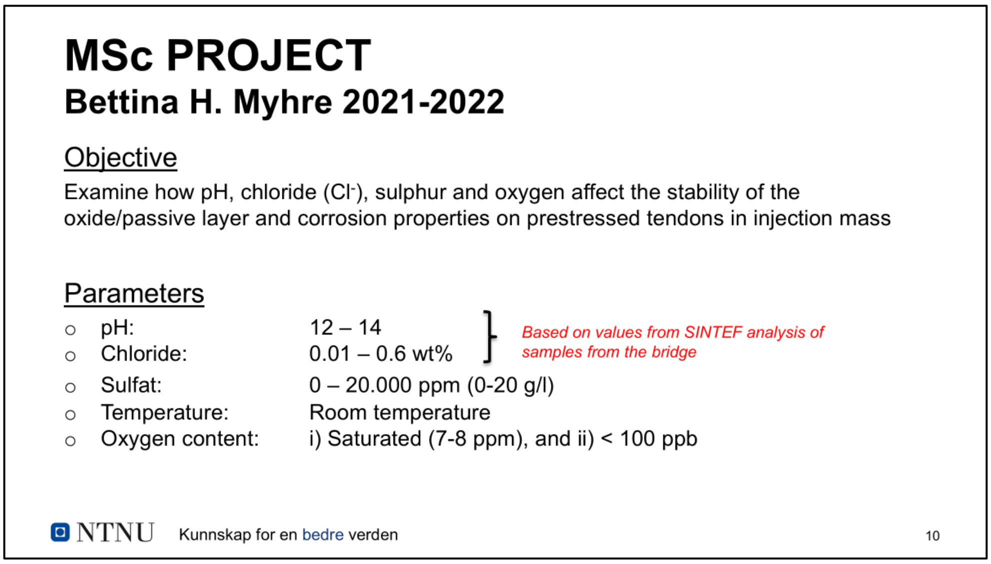
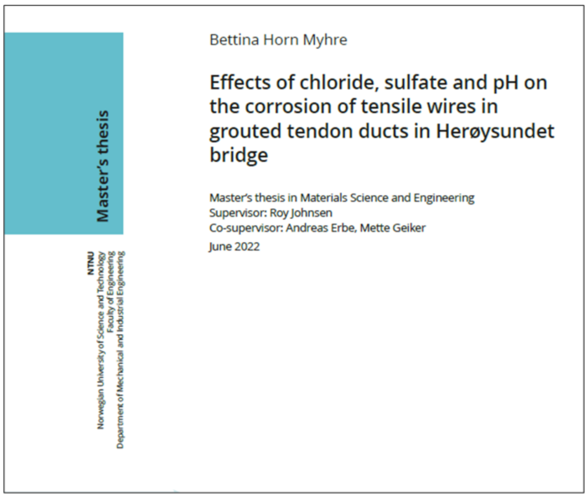




2 SUMMERY OF OUTCOME FROM MSc PROJECTS

2.1 MSc student Bettina Horn Myhre[3]




Master's thesis

Bettina Horn Myhre

Effects of chloride, sulfate and pH on the corrosion of tensile wires in grouted tendon ducts in Herøysundet bridge

Master's thesis in Materials Science and Engineering
Supervisor: Roy Johnsen
Co-supervisor: Andreas Erbe, Mette Geiker
June 2022

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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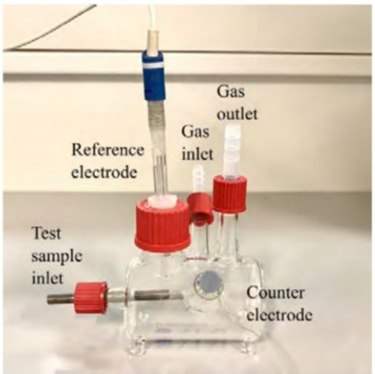
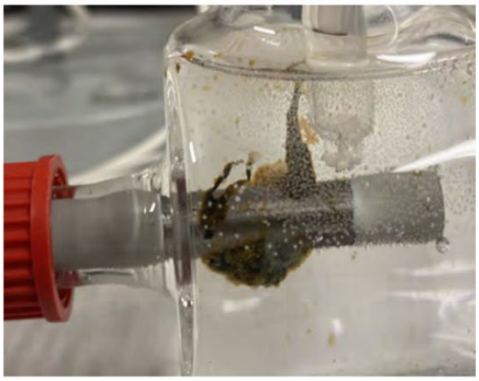
TEST SET-UP





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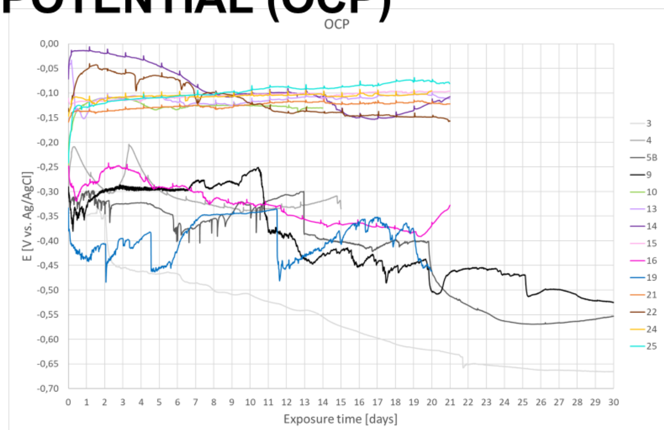
DEVELOPMENT OF CORROSION POTENTIAL (OCP)



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SAMPLES AFTER EXPOSURE

Samples[1]	Percentage of Area Corroded [%]	
	After OCP/LPR	After OCP/LPR + Polarization
4[2]	90-95	x
3	50-55	95-100
5B	20-25	95-100
9	10-15	x
19	0-5	25-30
14	0-5	0-5
25	0	5-10
25[3]	0	x
15	0	
15[3]	0	
21	0	
22	0	
10	0	
13	0	
16	0	
24	-	0

Solution	pH	Cl⁻ (M)	Cl⁻ (g/L)	SO_4^{2-} (M)	SO_4^{2-} (g/L)
3	12	0,4	14,18		
4	12,5	0,1	3,545		
5B	12,5	0,1	3,545		
9	12,5	0,1	3,545	0,2082032	20*
10	12,5				
13	12,5	0,001	0,036		
14	13	0,001	0,036		
15	12,5	0,01	0,36		
16	13	0,01	0,36		
19	12,5	0,1	3,545	0,2082032	20**
21	12,5	0,005	0,17725		
22	12,5	0,0075	0,265875		
24	13	0,005	0,17725		
25	12,5	0,01	0,3545	0,2082032	20**

*Na2SO4 **MgSO4

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CONCLUSIONS
Bettina H. Myhre

1. The chloride content is most important for initiation of corrosion, however, in combination with pH is also important.
2. pH 12.5 combined with 0.36 g/l chloride result in corrosion. However, at 0.036 g/l chloride and pH 12.5 corrosion is not initiated.
3. Addition of sulphate (Na_2SO_4 eller $MgSO_4$) did not effect initiation of corrosion (with the tested comcentrations).
4. Effect of oxygen not documented through the test program.

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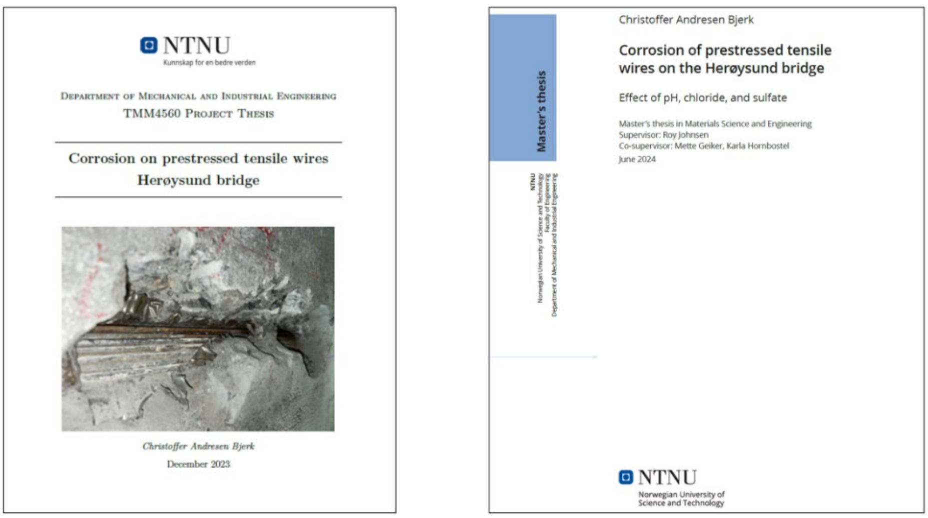
2.2 MSc Student Christopher Andresen Bjerk[5]



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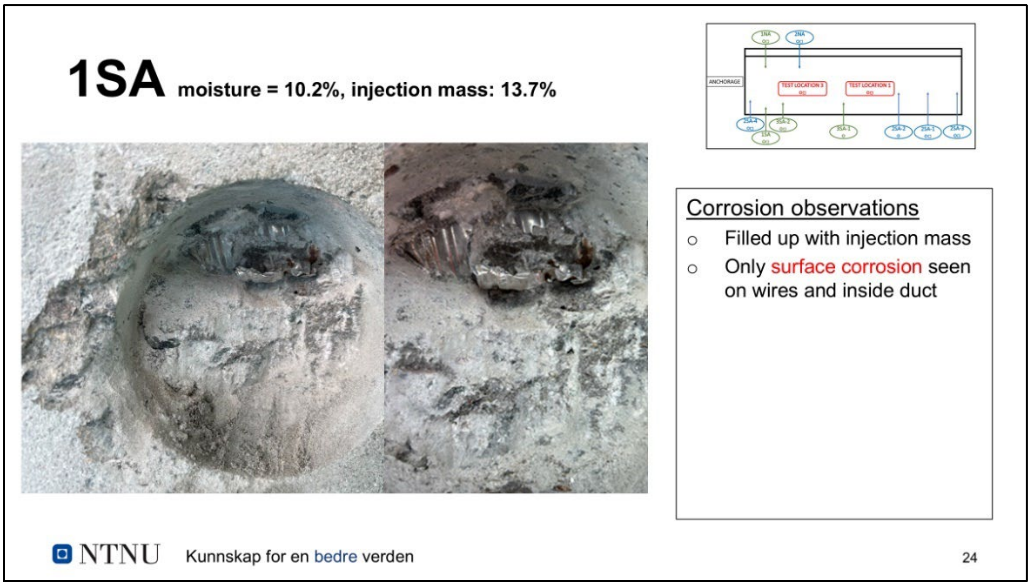
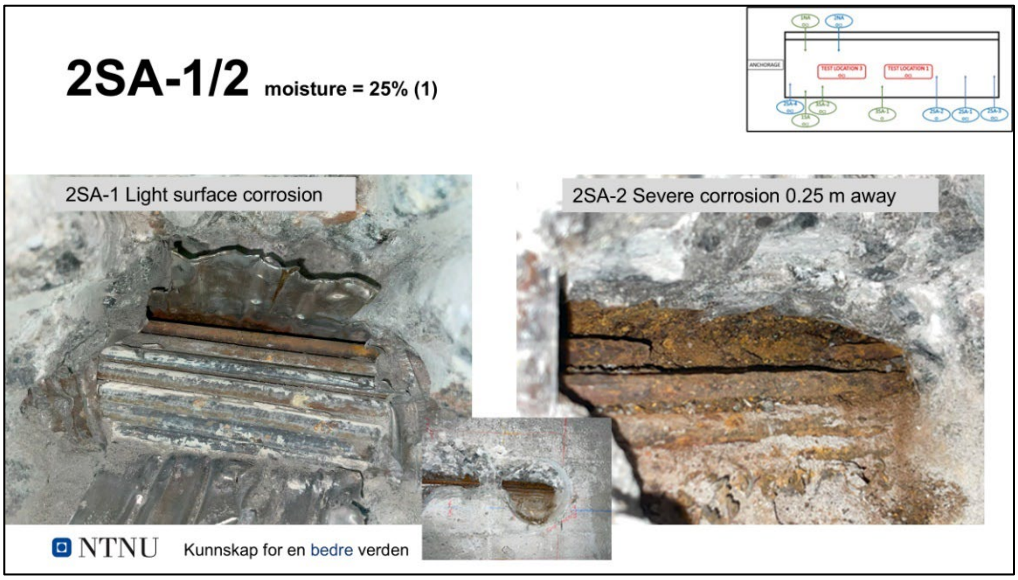
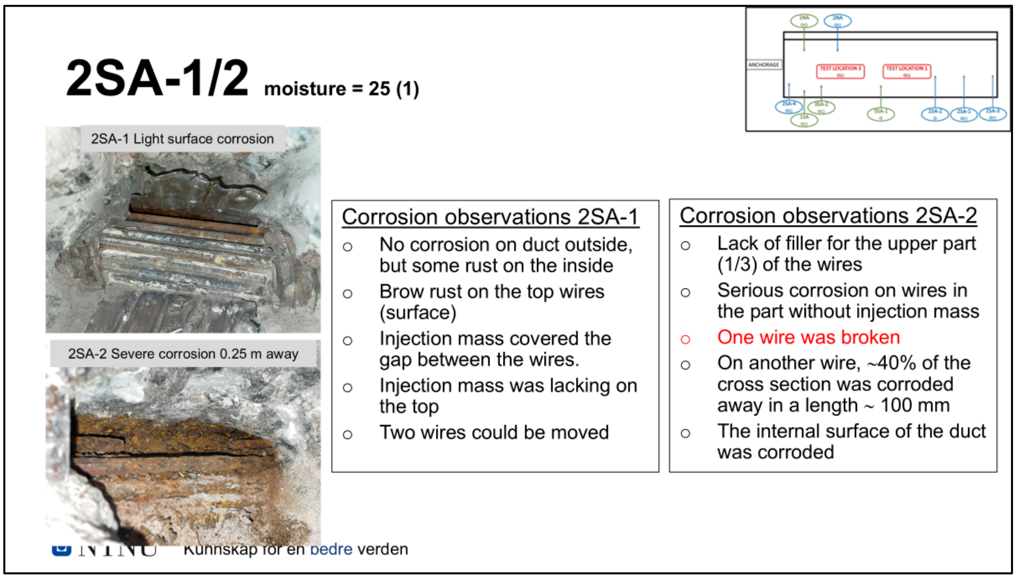
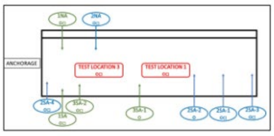
2.2.1 Results from inspection on Herøysund Bridge[3, 5]







2SA-3 Cl^- = 0.07%, moisture = 10.2%, injection mass: 1



Corrosion observations

- Injection mass between the wires, but lacking in the top
- Surface rust, but production marks could be seen
- Internal corrosion of the duct on the top, and also further down

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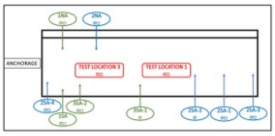
2SA-4 pH= 12.44 (PW), Cl^- = 0.039%, moisture = 45.1%, injection mass: 2



Corrosion observations

- «Wet» injection mass covering the wires and the volume between wires
- Light surface corrosion on wires, but production marks could be seen
- Slight corrosion on the inside of the duct

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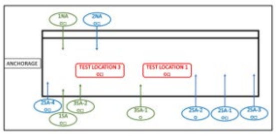
3SA-1



Corrosion observations

- No injection mass
- Some shallow surface corrosion (production marks could be seen)
- Indication of local corrosion attacks on wire(s) in the bottom of the duct
- Internal corrosion of the duct

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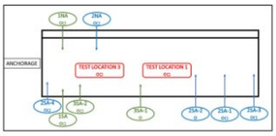
3SA-2 pH= 13.76 (PW), moisture = 10.8%, injection mass: 2



Corrosion observations

- Bitumen tape covering the outside of the duct (?)
- Shallow corrosion on the duct under the Bitumen tape
- Internal corrosion of the upper part of the duct
- Brow rust on the upper wire, but no/shallow attacks were seen (rust layer due to corrosion of the duct?)

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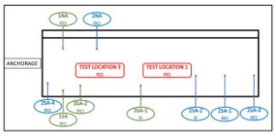
1NA moisture = 9.2%, injection mass: 1



Corrosion observations

- Completely filled with injection mass
- No corrosion observed (wires and duct)

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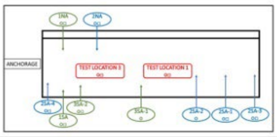
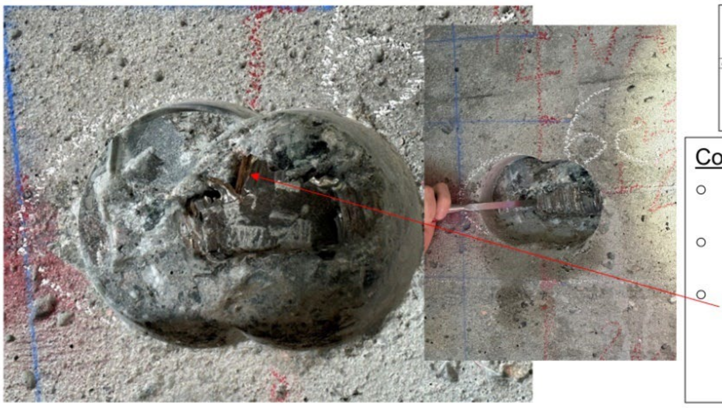
2NA pH=14.1 (PW), Cl^- = 0.061%, moisture = 10.2%, injection mass: 1





Corrosion observations

- Completely filled with injection mass
- No corrosion observed on wires
- Indication of corrosion on duct

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Post-tensioned components	Visual Observations after removal of concrete	Prior Inspections, Appendix B,C,D						Recent Inspections, Appendix A									
		2017	January 2020	August 2020				August 2023									
		NA	NA	NA	TL-1	TL-2	TL-3	1SA	2SA-1	2SA-2	2SA-3	2SA-4	3SA-1	3SA-2	3SA-16	1NA	2NA
Wire	Wires adhered to filler material			✓	✓	✓			✓					✓		✓	✓
	Surface corrosion				✓		✓	✓	✓		✓	✓	✓		✓		
	Non-uniform and pitting corrosion		✓		✓	✓				✓			✓				
	Wire breakage		✓				✓			✓							
	Presence of loose wires					✓			✓								
Duct	No corrosion			✓		✓										✓	✓
	Internal corrosion				✓		✓	✓	✓		✓	✓	✓				
	External corrosion																
	Both internal and external corrosion		✓			✓				✓				✓			
Filler Material	Fully grouted			✓				✓				✓		✓		✓	✓
	Presence of voids		✓		✓	✓	✓		✓		✓		✓		✓		
	Moist grout						✓			✓		✓					
	Frost damaged				✓		✓										
	White injection mass								✓	✓	✓	✓					
Mild steel	Corrosion			NA	NA	✓		NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	No signs of corrosion						✓										

OBSERVATIONS – FOR DISCUSSION

From the litterature

The following elements are important for initiation of corrosion

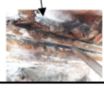
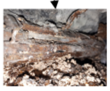
- pH, chloride content, sulphide, oxygen, temperature, humidity

Observations from Herøysund Bridge

- **2SA-4,** pH= 12.44 (PW), Cl^- = 0.039%, moisture = 45.1%, injection mass: 2 → *minor corrosion*
- **2SA-3,** Cl^- = 0.07%, moisture = 10.2%, injection mass: 1 → *minor corrosion*
- **3SA-2,** pH= 13.76 (PW), moisture = 10.8%, injection mass: 2 → *minor corrosion*
- **2NA,** pH=14.1 (PW), Cl^- = 0.061%, moisture = 10.2%, injection mass: 1 → *no corrosion*
- **Location 3 (2020),** pH=13, Cl^- = 0.037%, moisture = 44% (wet) → *serious corrosion + wire fracture*
- **Location 1 (2020),** pH=13, Cl^- = 0.035%, moisture = 21% (dry) → *serious corrosion*





HOW CAN WE EXPLAIN THE CORROSION ATTACKS ON THE HERØYSUND BRIDGE?

- Lab tests in simulated pore water have documented that pH and chloride content are two important parameteres
- Observations and analysis from the bridge show that similar pH, chloride content and moisture give different results:
  - 2SA-3 and 2SA-4 Minor surface corrosion
  - Location 1 and 3 Serious corrosion attack
- What can be the reason for the observations?
  - Local variation in injection mass quality (coverage, humidity, …)
  - Can other information from the SINTEF reports contribute in explaining the reason (pore water composition, TGA output, XRD)?
  - Local galvanic cells

2.2.2 Results from experimental work[5]

MSc Student Christopher – 2023/24

OBJECTIVES

a) How do different pH, chloride, and sulfate concentrations affect the corrosion of tensile wires?

b) How does oxygen affect the corrosion behavior of tensile wires?

c) How does the carbonation of a solution affect the corrosion behavior of tensile wires?

d) Are the corrosion properties of steel embedded in concrete different from steel that is not in concrete in a given solution?

e) If a steel sample and a steel sample embedded in concrete were connected and placed in the same solution, would it be possible to observe a galvanic effect?

f) Can the corrosion observed in the tension wires on the Herøysund bridge be explained by the findings from the executed test program?

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LONG TERM EXPOSURE TEST

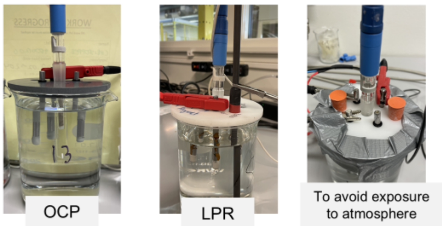
Solution	Starting pH	Cl^- [M]	$SO4^{2-}$ [M]
M1	12,5	0,005	-
M2	13	0,005	-
M3	13	0,01	-
M4	13	0,02	-
M5	12,5	0,005	0,01
M6	12,5	0,005	0,1
M7	12,5	0,005	0,2
M8	13	0,05	-
M9	13	0,1	-
M10	13	0,02	0,2
M11	12,5	0,005	0,1
M12	12,5	0,005	0,005
M13	12,5	0,005	0,007
M14	13	0,02	0,05
M15	13	0,02	0,1
M16	13	0,01	0,1
M17	12,5	0,005	-
M18	12,5	0,01	0,01
M19	13	0,02	0,01
M20	13	0,01	0,05
M21	13	0,01	0,2
M22	13	0,005	0,1

Goals

a) To determine how the OCP (corrosion potential) developed over time for a given sample in different solutions.

b) Determine the corrosion rate after a long exposure time (3 -5 weeks) with LPR measurements.

c) Determine through visual examination whether corrosion has occurred and, if so, identify the areas affected after a long exposure time (3 - 5 weeks).



OCP LPR To avoid exposure to atmosphere

NTNU Kunnska 0.005M = 0.18 g/l = 0.018%

LONG TERM EXPOSURE TEST

Observation: Lowering of potential with time

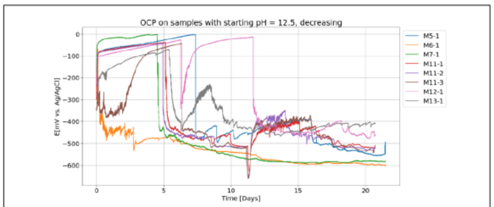


Figure 5.4: Corrosion potential for samples, in solutions with starting pH of 12.5, over time. The pH of these solutions decreased throughout the experiments.

At the end: pH 10-11

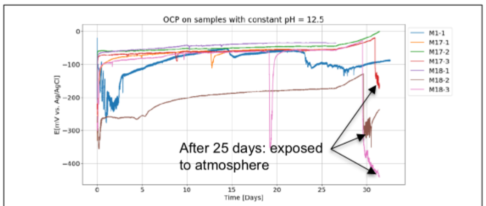


Figure 5.5: Corrosion potential for samples, in solutions with constant pH of 12.5, over time.

At the end: pH 12.5

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(a) Sample M5-1

(i) Sample M7-3

(e) Sample M6-2

(m) Sample M9-1

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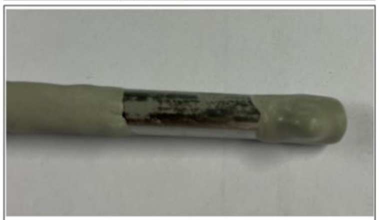
(i) Sample M19-3

(o) Sample M21-3

(k) Sample M20-2



(p) Sample M22-1

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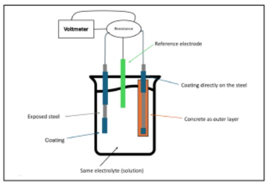
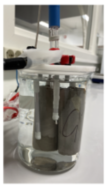
GALVANIC COUPLING

Steel embedded in concrete coupled to steel

Solution	Starting pH	Cl^- [M]	$SO4^{2-}$ [M]
G1	12,5	0,02	-
G2	12,5	0,02	-
G3	12,5	0,02	0,1
G4	12,5	0,01	0,2
G5	13	0,02	0,1
G6	13	0,05	0,1
G7	12,5	0,02	0,1





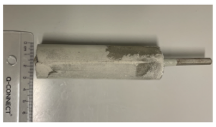
GOALS

a) To determine how the OCP (corrosion potential) developed over time for a coupled pair of samples. This includes one sample embedded in concrete and one sample directly in contact with the solution.

b) To determine if there is a current between two samples, one in concrete and one directly in contact with the solution.

c) To determine if there are any corrosion differences between an exposed area ratio between the concrete sample and the other sample if the ratio is 1:1 or 10:1, concrete:non-concrete.

d) After a longer time of exposure, examine the sample surface to see if corrosion occurred and if it did, where.



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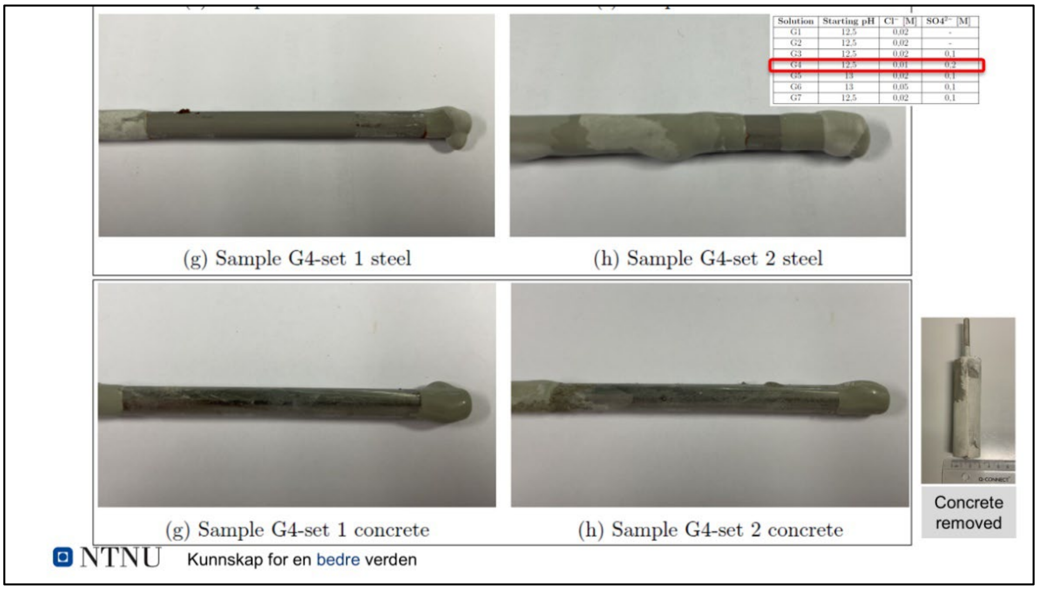

3 CONCLUSIONS

1. At a lower pH (12.5) the solution became more corrosive compared to at a higher pH (13).
2. *At a pH of 12.5 and no sulfate, corrosion initiated with a chloride concentration of 0.005 M. In solutions with a pH of 13 and no sulfate, a threshold between 0.02 and 0.005 M chloride was observed, where corrosion did not occur and where it did occur*. It was also observed that with increasing chloride concentration at both pH levels, the corrosiveness increased.
3. *At a pH of 12.5 and a chloride concentration of 0.005 M, the addition of a small amount of sulfate had a significant impact, making the solution more corrosive*. *At a pH of 13 with the same chloride concentration, a much larger amount of sulfate was required to achieve the same increase in corrosivity*. At both pH levels, it was observed that the corrosion properties did not change significantly beyond a certain concentration of sulfate.
4. With a *combination of chloride and sulfate in the solution*, it was observed that the corrosivity increased further compared to when only chloride was present.
5. For most of the samples where corrosion was seen, it primarily occurred at the interface between the coating and the exposed steel.
6. The effect of using sealed and open containers was significant. ***Open containers led to carbonation of the solution*** (decrease of the pH) and oxygen supply. Both factors led to a more corrosive solution.

4 FURTHER WORK

There are still uncertainties related to give a clear explanation of the reason(s) for the corrosion failures on the wires. Based on the executed work in the two MSc thesis projects, the follow proposal for further work is given:

1. From the long-term exposure experiments, it was seen that corrosion was initiated at the interface between the coating and the exposed steel. This might be because of crevice corrosion and needs further investigation.
2. To gain a better understanding of the galvanic experiments conducted, it is recommended to measure OCP and take LPR of freely exposed samples equivalent to those tested in the galvanic experiments and in the same solutions. This will help assess the effect of the measured galvanic current.
3. For a better understanding of the condition of the samples from the galvanic experiments, it is recommended to measure the anodic and cathodic polarization curves at the end of the tests on the same samples and solutions as in this project. This will give more insight into whether the samples are in a passive or active state.

4. Another suggestion for future research is to thoroughly explore the existing literature on galvanic coupling in prestressed reinforcement, given the limited information available. Based on these findings, it should be determined if the galvanic experiments should be modified and conducted over different time periods to produce more field-relevant results for galvanic couplings.

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